SCIENCE FOR EVERYONE

G.S. VORONOV

STORMING THE FORTRESS OF FUSION

MIR

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for Everyone

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Storming the Fortress of Fusion

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Preface to the English Edition

This book is about one of the extensive and far-reaching topics in the physics of the 20th century, the problem of controlled nuclear fusion.

Research on controlled nuclear fusion began in the early 1950s after thermonuclear bomb tests demonstrated the feasibility of uncontrolled fusion.

However, unlike atomic energy for which the road from the first atom bomb tests to nuclear power plants took only several years, it has been incredibly difficult to tame fusion energy. So difficult has this task been that even now, some 35 years later, we may only say that the efforts of thousands of scientists from all over the world have led to a solution that is possible in principle. A practical realization, viz. the construction of a fusion power plant that can compete with thermal and nuclear ones, still lies some 10-15 years in the future.

It may seem from this description that the choice of title with the word "storming" was not entirely appropriate and that perhaps the word "siege" would have been better. However, the search for controlled nuclear fusion has been very intense and indeed the word "storming" is the most appropriate. In the three years separating the publications

of the Russian and English editions almost all the major approaches have advanced.

The main avenue of work, on tokamaks, has been brought close to the eagerly awaited goal. The needed plasma temperature, which must be attained in a future reactor, is 100 million degrees Kelvin and it has been achieved in several large tokamaks in the USA, USSR, Europe, and Japan. The plasma densities and confinement times have got "just a little bit" (a factor of 2-3) to go, which should take a couple of years. We may now with some confidence expect a significant event around 1990, namely, the ignition of a self-sustaining fusion reaction in a tokamak plasma.

This will be a crucial moment for fusion research in that the feasibility of the generation of fusion energy will be proved experimentally. It will also signal the end of the purely scientific stage in the investigation. Clearly, a range of engineering and economic difficulties remain unaddressed, and even questions of physics too remain unanswered, however the principal problem, against which physicists have battered for decades, will have finally been resolved.

Therefore this is an appropriate time to survey the long path it has taken scientists forty years to trace in order to arrive at the successes of today. This path has not been easy and sometimes it has been dramatic. It is astounding to see how many obstacles

have been overcome, to assess the rich number of strategies and ideas that have been tried during the investigations. Such a survey is the aim of this book.

International cooperation between scientists from many countries has played a very important role during the whole period these investigations have proceeded. The spirit of this cooperation has sustained all the research during these difficult decades, nor has the cooperation ever been interrupted, even during the gloomy years of the "cold war" and confrontation.

I would be happy if the English translation of this book helps to promote and strengthen this cooperation.

December, 1987 *Gennady Voronov*

Preface to the Russian Edition

For more than thirty years scientists from all over the world have been working on controlled nuclear fusion. The heart of the problem is to arrange for the fusion reaction that transmutes hydrogen into helium, the reaction that powers the Sun and the stars, to take place on Earth.

When this can be done, humanity will have overcome the energy problem for ever. In contrast to oil, coal, and even uranium, the reserves of which are disappearing before our eyes, the reserves of hydrogen in the oceans are practically infinite. They will last millions of years whatever humanity's energy needs may be.

The word "controlled" is important in this context because uncontrolled fusion has taken place, namely, during the explosion of a hydrogen bomb. In order to rescue humanity from energy starvation, a way must be found to control fusion reactions, and to make them proceed peacefully, giving off their energy gradually. An American scientist put it this way: humanity will certainly be able to control nuclear fusion if it does not die of uncontrolled fusion first.

Controlling fusion reactions is incredibly difficult, so much so that a solution may only be found in the foreseeable future by the combined effort of the whole of humanity. It is also a project that affects all countries. That is why beginning with 1956, when Soviet scientists took the initiative

and the veil of secrecy was lifted, this research area has been close and fruitful international cooperation.

This book is dedicated to the memory of my teacher, Matvei Samsonovich Rabinovich, a great scientist and charming person who devoted over twenty years of his life to fusion investigations. His scientific inight, courage, and optimism were most clearly manifested in the stellarator programme, now a promising approach to controlled fusion. Matvei Rabinovich's bon viveur, well wishing, and charming nature contributed in no small degree to the unique atmosphere of cooperation amongst those working on controlled fusion.

During the thirty years humanity has spent on controlled fusion every new development in physics and technology has been utilized. Several branches of physics, particularly plasma physics, have been substantially advanced by the research on nuclear fusion. An informal account of the dramatic development of these investigations is therefore difficult.

It is my pleasant duty to thank V.D. Shafranov, Corr. Mem. USSR Acad. Sc., V.A. Chuyanov, D.Sc. (Phys.-Math.), and I.S. Shpigel', D.Sc. (Phys.-Math.), for their careful reading of the manuscript and their valuable comments.

Gennady Voronov

Chapter 1

Nuclear Fusion

Top-Secret Investigations

Sensational revelations astounded the world in the spring of 1956. The eminent Soviet physicist I.V. Kurchatov, who was leading the Soviet Union's research efforts on the atom and hydrogen bombs, was visiting the UK as part of an official delegation. In a lecture delivered at the Harwell Atomic Research Centre on the fundamental investigations being carried out in the USSR, he revealed that attempts were being made to harness the nuclear reactions occurring in a hydrogen bomb for peaceful purposes, viz. to generate electricity. This fine Soviet example was emulated by the UK and the USA: the veil of secrecy had been lifted!

At three successive international conferences between 1956 and 1958, scientists from different countries shared the results of investigations that had been carried out for many years in utmost secrecy.

The Emergence of the Problem

Thermonuclear reactions, or the reactions of nuclear fusion, were discovered as early as in the 1930s during research into the

source of energy that powers the Sun and other stars.

During the fusion reactions that occur in stars, hydrogen nuclei combine to form helium nuclei. This process is accompanied by the liberation of an enormous amount of energy, which we receive from the Sun in the form of light and heat. However, these reactions can only proceed at temperatures of tens of millions of degrees Kelvin.

When the reactions were discovered and the source of stellar energy was revealed, the practical application of fusion reactions on Earth could not be imagined. There was no way of creating temperatures on Earth of the order of tens of millions of degrees Kelvin.

As the years passed, however, and the Second World War was coming to an end, the most lethal of all weapons ever to exist on Earth, the atom bomb, was created.

In studies of the physical processes which occur when an atom bomb explodes, it was revealed that the energy released during the fission of uranium is so large that the temperature may rise to millions of degrees Kelvin. Naturally this result at once reminded the scientists about the fusion reactions which require just this temperature. It was proposed that an atom bomb be used as a "matchstick" to trigger a fusion reaction and thus considerably increase the energy of the explosion.

The idea worked and in a few years the world was rocked by test explosions of thermonuclear (fusion) or, as they were called at that time, hydrogen bombs, the energy of the explosions being equivalent to tens of millions of tons of the conventional explosive TNT.

Looking at the things from a different point of view, we can state that the energy of explosion of a hydrogen bomb is equal to the energy it takes all the electric power plants throughout the world one week to generate. This comparison led naturally to a marvellous idea: what if we could make a hydrogen bomb explode slowly over a period of one week and use the heat liberated to generate electricity? Just imagine the amount of coal, oil and natural gas consumed by all those power plants in the course of one week. And all this could be replaced by just a few tons of hydrogen! However, the nuclear fusion would have to take place slowly and in a controlled manner, rather than in the form of an explosion. In other words, we must learn how to control fusion reactions. This is the problem of controlled thermonuclear fusion.

Suppose that we learn how to control nuclear fusion and a fusion reactor has been created. What will this give? What advantages would thermonuclear power have and how much would there be?

The first and foremost advantage we have

met: thermonuclear power would solve our energy crisis. Unlike conventional power engineering, which threatens to exhaust our reserves of oil, gas, coal and uranium, thermonuclear power would be derived from hydrogen, the reserves of which in our oceans are practically unlimited. (To be more precise, a fusion reactor will operate on an isotope of hydrogen, viz. deuterium, and in nature there is one part of deuterium to 6800 parts of normal hydrogen.) In addition, lithium will be required. However, even if we take this into account, the reserves of fusion fuel are enormous and their extraction is comparatively cheap. The maximum amount of energy that can be generated on Earth without risking a climatic catastrophe is limited to just about 1% of the solar energy incident on the Earth. At this rate, the reserves of deuterium in the ocean should suffice for about 300 million years.

The second important advantage of thermonuclear power is its ecological cleanliness. Neither the extraction of the starting materials (deuterium and lithium) nor the waste product (inert gas helium) poses any threat to the environment. The only cause of concern are the neutrons produced during the generation of power. However, the neutrons themselves are absorbed within the reactor, and the risks of stray radioactivity can be reduced to minimum by an

appropriate choice of construction materials. Fusion reactions simply do not produce highly radioactive materials such as are produced by uranium fission.

The third advantage of fusion reactors is that they do not produce any thing which could be used to manufacture nuclear weapons. Hence there is no danger of the proliferation of nuclear weapons from the extensive use of fusion reactors.

Finally, the fourth advantage is that even high-power fusion reactors would only be handling small energy reserves and quantities of the working substances. Hence the danger of an explosion is virtually eliminated and the risk of the radioactive contamination of the environment in the event of an accident is very low.

These advantages are so significant and so obvious that nuclear fusion research has been one of the most important branches of modern scientific endeavour right from the time nuclear fusion was first mooted. Although all the leading industrial nations of the world have devoted considerable resources to this project, it has turned out to be unbelievably complicated. The task is so complex that only now, after three decades of extensive research in an atmosphere of cooperation among scientists from all over the world, can we safely regard controlled nuclear fusion to be possible in principle.

Had physicists been aware of the true scale of the obstacles to thermonuclear power engineering, they would probably have lacked the courage to take up the investigation.

In order to get some idea of the difficulties, we must know the structure of the atomic nucleus, the way in which nuclear reactions proceed, and the source of nuclear energy.

Structure of the Atomic Nucleus

Nature seems to be an infinite regression, and nuclear physicists continue to try to penetrate deeper and deeper into the structure of the nucleus. The situation is reminiscent of a Russian doll: the nucleus consists of protons and neutrons, which consist of quarks, which consist of ... and so on. However, we need not go into these details in order to address the subject of our discussion. We shall assume that the nucleus consists of protons and neutrons between which nuclear forces act. These forces are very strong: the attractive force between two protons 10^{-15} m apart is much stronger than the Coulomb repulsive force between the two like-charged particles.

A peculiar feature of the nuclear forces is that they decrease rapidly with increasing distance. Hence, in order to induce a nuclear reaction, we must bring together the parti-

cles participating in a reaction to distances of about 10^{-14}-10^{-15} m. This is one of the enormous difficulties facing controlled fusion. We shall return to this question later. For the present, let us consider the source of nuclear energy.

Where Does Nuclear Energy Come from?

The simplest nucleus is the nucleus of a hydrogen atom and is formed by just one proton. The energy contained in this nucleus can be easily calculated using Einstein's mass-energy relation $E = mc^2$. The mass of a proton is $m_p = 1.67 \times 10^{-27}$ kg and the velocity of light is 3×10^8 m/s. This gives $E = 1.5 \times 10^{-10}$ J or 938 MeV.*

This is a very large amount of energy. Under normal conditions, one cubic metre of hydrogen contains 2.7×10^{25} molecules of H_2, i.e. 5.4×10^{25} protons. The total energy contained in 1 m^3 of hydrogen is 8.1×10^{15} J or 2.25×10^9 kwhr. This is comparable with the total amount of electricity generated daily in the USSR. In 1985, about 15.4×10^{11} kwhr of electricity was generated in the USSR. Thus, if we could completely extract the energy contained

* 1 MeV = 10^6 eV (electronvolt). The electronvolt is the unit of energy employed in atomic physics (1 eV = 1.6×10^{-19} J). This is the energy of thermal motion of a particle at a temperature of 11 600 K.

in atomic nuclei about 7×10^2 m^3 or 64 kg of hydrogen would be sufficient to generate all the electricity the USSR require in one year.

Unfortunately, the only way of completely extracting the energy contained in atomic nuclei is by combining them with antimatter nuclei. The collision of a proton p and an antiproton $\bar{p}$ results in their annihilation, and the energy liberated is completely transformed into the energy of γ-quanta: $p + \bar{p} \rightarrow \gamma + \gamma$. The γ-quanta could then be absorbed in a thick layer of matter and the heat released can be employed to produce electricity. There is only one flaw—there is no source for sufficient quantities of antiprotons. Hence this method cannot unfortunately be used for practical purposes.

Let us now consider how energy can be extracted from more complex nuclei. All the nuclei of the atoms of a given element contain the same number of protons, which is the atomic number of the element in the Periodic Table. Different atoms of the same element may, however, contain different number of neutrons in their nuclei. These atoms are called isotopes.

By convention, all the isotopes of a given element are denoted in physics by the same chemical symbol. In order to distinguish the isotopes from one another, the total number of neutrons and protons in the nucleus,

i.e. the mass number A of the nucleus, is written as a superscript on the left of the symbol. In order to clarify the situation still further, the number Z of protons, i.e. the atomic number of the element, is also written as a subscript on the left. For example, ${}^3_2He$ and ${}^4_2He$ are both isotopes of helium. The nuclei of both isotopes contain 2 protons and hence occupy the second position in the Periodic Table. But the isotope ${}^3He$ contains only three particles in its nucleus, viz. two protons and one neutron, while ${}^4He$ contains 4 particles, viz. 2 protons and 2 neutrons. Since the masses of protons and neutrons are nearly equal, the atom of the ${}^3He$ isotope is about three times heavier than a hydrogen atom, while a ${}^4He$ atom is four times heavier. Accordingly, deuterium and tritium, the isotopes of hydrogen, should be denoted by the symbols ${}^2H$ and ${}^3H$, respectively. In practice, however, they are often denoted by the symbols D and T without superscripts.

To measure the atomic masses, an atomic mass unit (amu), equal to 1/12 of the mass of the carbon isotope ${}^{12}C$, is used in atomic physics. In terms of these units, the masses of the constituents of an atom are: electron mass $m_e = 0.000548$ amu, proton mass $m_p = 1.007276$ amu, and neutron mass $m_n = 1.008665$ amu. A curious phenomenon now arises. Although the combined masses of a proton and an electron

the particles comprising a hydrogen atom, more or less equal the mass of a hydrogen atom, we find there is a paradox for more complex atoms: the mass of the atom is much lower than the summed free masses of its constituent particles. For a helium atom, the sum of the masses of the two protons, two neutrons, and two electrons is 4.0330, while the mass of a helium atom is 4.0026. For tritium, the masses of the constituents sum to 3.2519 instead of the atom's mass of 3.0165, while for deuterium the constituents sum to 2.0165 instead of the atom's mass of 2.0141. Does this mean the law of mass conservation is violated? Moreover, by Einstein's mass-energy relation $E = mc^2$, the law of energy conservation seems to be violated too. Actually, this is not so. By simply adding together the masses of the particles constituting a complex nucleus, we have neglected the energy liberated in the process. This, by the relation $E = mc^2$, leads to a mass deficit. When protons and neutrons combine to form a nucleus, energy is liberated either in the form of an emitted particle, a photon, or as the kinetic energy of the particles formed during the reaction. If this energy is taken into account, the laws of mass and energy conservation will be found to be valid.

The energy we had not taken into account and which led to the apparent paradox is called the binding energy. It appears as

a result of the work done by the nuclear forces to form the bound system, the nucleus, from a number of particles that were free.

In fact, this is quite an ordinary phenomenon which we encounter everyday. When a stone falls to the ground, a bound stone-Earth system is formed and the binding energy is liberated in the form of heat or damage to the ground. When wood is burnt in a fireplace, a bound system is formed as carbon and oxygen atoms combine into CO_2 molecules. The binding energy (about 1 eV per molecule) is released in the form of heat and the mass of the CO_2 molecule is found to be less than the sum of the masses of the carbon and oxygen atoms by some 1 eV/c^2. However, the change in the mass due to the liberation of the binding energy in the systems formed by the stone and the Earth or by the carbon and oxygen atoms is negligibly small and hence it escapes our notice.

The energy, however, is clearly distinguishable in nuclear reactions. A cubic metre of deuterium is 1.14 g heavier than a cubic metre of helium, although in both cases the number of protons, neutrons, and electrons per cubic metre is the same. By measuring the change in mass, we can also measure the binding energy of other nuclei. These measurements are given in Fig. 1.1. With the help of the relation $E = mc^2$, the

binding energy can be calculated from the mass difference. In order to compare nuclei containing different number of particles, the binding energy should be divided by the mass number A of the nucleus. The result,

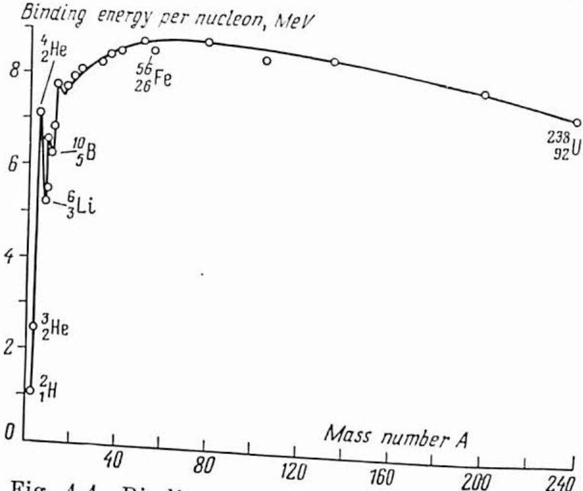


Fig. 1.1. Binding energy per nucleon vs. mass number A.

the binding energy per particle in the nucleus (nucleon), versus the mass number A is shown in Fig. 1.1. It can be seen that the binding energy increases steadily with A, to begin with. This growth becomes slower at $A \simeq 40$ (argon), and the iron nucleus has the largest binding energy. As the number of particles in the nucleus increases further, the binding energy begins to decrea-

se. This is because some of the many particles in the nucleus are separated from each other by distances comparable with the range of the nuclear forces, and so the attraction between them is small. Moreover, as the number of protons increases, the energy of their Coulomb repulsion also increases. Towards the end of the Periodic Table, e.g. for thorium or uranium, the binding energy is considerably lower than it is for the iron nucleus.

It can be seen at once from Fig. 1.1 that nuclear energy can be liberated in two ways. We can either combine light nuclei, like hydrogen or deuterium, into heavier nuclei or, conversely, split heavy nuclei, like uranium, into fragments with $A \simeq 60$ and so have nuclei with the highest binding energy. Nuclear reactions in which a heavier nucleus is formed from lighter nuclei are called fusion reactions. It can be seen from Fig. 1.1 that any nuclei from hydrogen to iron can be used to obtain energy by nuclear fusion. Reactions involving the splitting of heavy nuclei are called fission reactions. Any nucleus from uranium down to iron can be used in a fission reaction.

Thus, we know the source of nuclear energy. Both in fusion and fission reactions, the source is the same, viz. the binding energy of the protons and neutrons in a nucleus, resulting from the action of nuclear forces.

Overcoming the Coulomb Repulsion

Historically, the fission reaction was the first to come to the service of mankind. Nuclear power plants based on the fission reactions of uranium and plutonium are already in operation, while the application of fusion to energy generation is only at the research level.

This is not surprising. The influence of electrostatic forces makes fusion reactions much more difficult to apply than the fission reactions. The Coulomb repulsion between the like-charged protons obstructs the nuclei from coming close together in fusion reactions. In fission reactions, on the other hand, the repulsive forces facilitate the escape of the fission fragments. Hence, in order to carry out a fusion reaction we must first overcome the electrostatic repulsion of the nuclei.

Naturally, the electrostatic repulsion is the larger, the larger the charge of the nucleus. According to Coulomb's law, in order to bring two nuclei with charges q_1 and q_2 to within a distance r of each other, we must spend energy

$$E = k\frac{q_1 q_2}{r},$$

where k is a constant depending on the units of measurement. (The absolute value of k in SI units is 9×10^9.) In order to

make two nuclei fuse, they must be brought close to within 10^{-14} m, at which point the effect of the nuclear forces becomes noticeable. Once this close together, the attraction due to nuclear forces will overcome the Coulomb repulsion and the nuclei will fuse. The energy of the electrostatic repulsion for hydrogen isotopes is about 0.15 MeV. This is a large amount of energy and only hydrogen nuclei heated to temperatures of about 1.6×10^9 K will possess such an energy on the average. Still higher temperatures are required for other nuclei. Hence, although it might seem from Fig. 1.1 that in principle nuclear energy can be obtained from fusion reactions involving any element from hydrogen to iron, the difficulties associated with overcoming of the Coulomb repulsion between the nuclei reduce the choice to the lightest nuclei, e.g. isotopes of hydrogen, helium and lithium. These elements can participate in a variety of fusion reactions, some of which are

$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{He} + \mathrm{n} + 3.3\ \mathrm{MeV},$$
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T} + \mathrm{p} + 4.0\ \mathrm{MeV},$$
$$\mathrm{T} + \mathrm{D} \rightarrow {}^4\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV},$$
$$\mathrm{D} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + \mathrm{p} + 18.3\ \mathrm{MeV},$$
$$\mathrm{D} + {}^6\mathrm{Li} \rightarrow 2\ {}^4\mathrm{He} + 22.4\ \mathrm{MeV},$$
$$\mathrm{p} + {}^7\mathrm{Li} \rightarrow 2\ {}^4\mathrm{He} + 17.3\ \mathrm{MeV}.$$

Which of these reactions is preferable? Each reaction involves the liberation of

a considerable amount of energy, running into millions of electronvolts. We showed that the energy required to overcome the Coulomb barrier in reactions involving two hydrogen isotopes is ~ 0.15 MeV, but for reactions with helium isotopes it is ~ 0.3 MeV, while in the case of lithium isotopes, about 0.5 MeV must be spent. In any of the above reactions, a gain in energy is possible in principle. The decisive factor governing the choice of reaction is whether the conditions under which the reaction proceeds at a rate of practical interest can be attained.

To begin with, let us consider the reactions taking place in the Sun and when a hydrogen bomb explodes.

What Goes On in the Sun?

Protons are the main fuel on the Sun. They fuse to form ^4He nuclei. This final result can be obtained via two reaction cycles, viz. the hydrogen cycle and the carbon-nitrogen cycle. The hydrogen cycle consists of four reactions:

Reaction	Energy liberated, MeV	Average time of reaction
$p + p \rightarrow D + e^+ + \nu$	0.4	1.4×10^{10} yrs
$e^+ + e^- \rightarrow 2\gamma$	1	10^{-19} s
$p + D \rightarrow {}^3He + \gamma$	5.5	5.7 s
${}^3He + {}^3He \rightarrow {}^4He + 2p$	12.85	10^6 yrs

At first, the two protons combine to form a deuterium nucleus or, as it is sometimes called, a deuteron D. This is accompanied by the formation of a positron e^+ and a neutrino ν. The neutrino flies away, carrying with it an energy of 0.257 MeV, while the positron and the nearest electron annihilate each other forming two γ-quanta and releasing another 1 MeV of energy. The γ-quanta are absorbed by the surrounding matter and hence this energy remains with the Sun. The deuteron formed in the first reaction combines with a proton to form a ^3He nucleus, releasing a further 5.5 MeV of energy. Finally, two of the ^3He nuclei fuse to form a ^4He nucleus and two protons, releasing 12.85 MeV of energy. A closed cycle is obtained if each of the first three reactions occurs twice. In all, an energy of 26.7 MeV is released in such a closed cycle, of which 0.5 MeV is taken away by the two neutrinos.

In the carbon-nitrogen cycle, the ^{12}C nucleus acts as a sort of catalyst. Four protons fuse into a helium nucleus in a cycle containing the following six reactions:

Reaction	Energy liberated, MeV	Average time of reaction
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	1.95	1.3×10^7 yrs
${}^{13}N \rightarrow {}^{13}C + e^+ + \nu$	1.57	7 min
$p + {}^{13}C \rightarrow {}^{14}N + \gamma$	7.54	2.7×10^6 yrs
$p + {}^{14}N \rightarrow {}^{15}O + \gamma$	7.35	3.3×10^8 yrs
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu$	1.73	82 s
$p + {}^{15}N \rightarrow {}^{12}C + {}^4He$	4.96	1.1×10^5 yrs

As a result of this cycle of reactions we again obtain a ^{12}C nucleus while the four protons form a ^{4}He nucleus. This is accompanied by the liberation of 25.03 MeV of energy, of which 1.7 MeV is taken away by the neutrinos. Let us now turn to the third column in the table. It shows the average reaction time calculated for the conditions prevailing in the Sun's interior, i.e. a temperature of 15 million degrees K and a hydrogen density of about 10^5 kg/m^3. Even by cosmic standards, 1.4×10^{10} yrs is quite a long time. During the life of the Sun (about 5×10^9 years), only a small fraction of the hydrogen existing on it has participated in the reaction forming the deuterium. It is also evident from the above tables that nature is also in no hurry to carry out some of the other reactions in both cycles. Hence nuclear energy is liberated at the Sun quite slowly, viz. at a rate of about 20 W/m^3. This is much smaller than the energy liberated by the human body, viz. about 200 W in a volume ~ 0.1 m^3, or 2000 W/m^3. Then why is the Sun so hot, you might ask. Primarily, due to its enormous size.

Obviously, it is meaningless to try to recreate on the Earth the conditions prevailing in the Sun and to implement the cycle of reactions that generate energy on the Sun. Instead, we must create conditions or choose reactions for which the rate of energy release is much faster.

And What Goes On in a Hydrogen Bomb?

Let us now consider the course of events during the explosion of a hydrogen bomb. The first stage during the explosion is a fission reaction involving uranium or plutonium. The heat liberated in this reaction raises the temperature to several million degrees Kelvin. At this point the isotopes of hydrogen, viz. deuterium and tritium, and the ^{6}Li isotope of lithium, which are also included in a hydrogen bomb, begin to participate in the following reactions:

$$D + D \rightarrow {}^3He + n + 3.3 \text{ MeV},$$
$$D + D \rightarrow T + p + 4.0 \text{ MeV},$$
$${}^6Li + n \rightarrow {}^4He + T + 4.8 \text{ MeV},$$
$$T + D \rightarrow {}^4He + n + 17.6 \text{ MeV}.$$

The very high temperature of the explosion is only maintained for a few millionths of a second. Hence the density of the materials used in the bomb must be maximum. In practice, solid compounds of lithium and deuterium or tritium, such as LiD or LiT, are used. Under these conditions, the rate of energy liberation is very high, of the order of 10^{17} J over a period of 10^{-5} s, i.e. $\sim 10^{22}$ W. This rate is much too fast for the practical application of these materials as energy sources. Indeed, the power of the largest power plants existing on the Earth is 10^{10} W.

Thus, the reaction to be used in a fusion reactor must be considerably faster than the reactions in the Sun but considerably slower than the reactions in a hydrogen bomb.

What Determines a Reaction's Rate?

Let us take any nucleus and try to involve it in a nuclear reaction. We have seen that, in the first place, we must overcome the Coulomb barrier. To do this, we impart a large velocity to the nucleus (say, v m/s) and direct it towards the target nucleus. Since the target nucleus is very small, it is not easy to hit it. The size of the "bull's-eye" must be of the order of 10^{-14} m, since this is the range of nuclear forces.

If, for simplicity, we assume the two nuclei to be rigid spheres of radii r_1 and r_2, a collision will take place only if the distance between the nuclei (spheres) is less than $r_1 + r_2$ at some instant. We can imagine the projectile nucleus as a disc of radius $R = r_1 + r_2$ and the target nucleus as a point, and assume that the reaction takes place each time this point is within the limits of the disc. The reaction rate can be easily calculated for this model: the projectile nucleus will cover a distance of v m in 1 s. The area of the disc is $\sigma = \pi R^2$, and hence a volume $V = \sigma v$ m^3 is formed along the trajectory of the projectile parti-

cle in which reactions can take place. If the density of the nuclei in the target is equal to n_2 nuclei/m^3, the volume will contain $n_2V = n_2\sigma v$ nuclei and hence $n_2\sigma v$ reactions will take place. If n_1 particles are emitted per second, the total number of reactions occurring per second will be equal to $n_1n_2\sigma v$.

In actual practice, the situation is much more complicated in nature: nuclei are not rigid spheres, the distance within which they must be brought together so that they could react together is determined by the competition between the nuclear and electrostatic forces and hence depends on the velocity at which the nuclei approach each other.

In order to calculate the reaction rate using this simple model, we introduce the concept of effective reaction cross-section and denote it by the same letter σ. Thus, the whole problem boils down to computation or measurement of σ. If σ is known, the reaction rate can be calculated according to the formula $n_1n_2\sigma v$ as in the simple model.

Figure 1.2 contains measured effective cross-sections of various fusion reactions as a function of the energy of the projectile particle. It can be seen that the reaction $D + T$ has the largest cross-section, i.e. up to 5×10^{-28} m^2. This is followed by the reactions $D + D$ and $^3He + D$, but their

cross-sections are about 100 times smaller than for the D + T reaction. Other reactions have even smaller cross-sections.

When the energy of the projectile particle is below 5 keV, the cross-sections of all

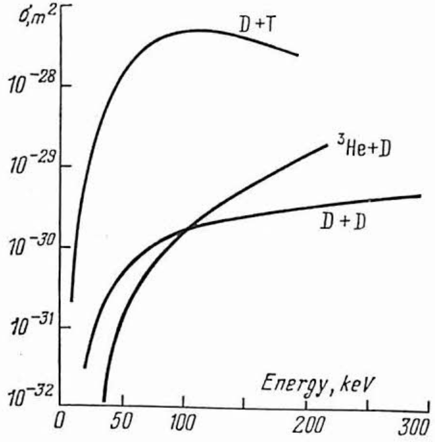


Fig. 1.2. Fusion reaction cross-section as a function of the energy of projectile nucleus.

the reactions are very small. They become significant only for energies of 50-100 keV. However, the energy liberated in fusion reactions is of the order of millions of electronvolts. Hence all these reactions are advantageous from the energy point of view. By spending a few hundred keV's to accelerate a nucleus, we obtain millions of electronvolts from a fusion reaction.

Hop, Step and Jump!

We move directly to the idea of using a simple setup, viz. a beam of accelerated nuclei and a target, to obtain energy from fusion. It is not difficult to create an accelerator, i.e. to impart an energy of several hundred electronvolts to a particle passing through two electrodes maintained at an appropriate potential difference. Hence a reactor operating on this system can be obtained easily and cheaply. But, unfortunately, it won't work.

When an accelerated nucleus hits the target, it not only triggers the fusion reaction we expect, but also a large number of many other processes, of which ionization is the worst. The electric field of a rapidly moving nucleus strips electrons off the target atoms, and 30-40 eV are spent on each act of ionization. This energy is much smaller than the energy of the accelerated nucleus, but the number of ionization acts might be large.

For ionization to occur, it is sufficient for the projectile nucleus to pass anywhere through the atom. The size of an atom is usually about 10^{-10} m, which means that the ionization cross-section will be about 10^{-20} m^2. It was mentioned above that the cross-section of nuclear fusion is much smaller, viz. $\sim 10^{-28}$ m^2. Hence the probability of ionization is 10^8 times greater than

that of a nuclear reaction. Consequently, each fusion reaction in which an energy of, say, 20 MeV is liberated, will be accompanied by 10^8 acts of ionization, which will involve an expenditure of 4 GeV of energy. Hence a reactor operating on a beam of nuclei hitting a target is quite unprofitable as it would only produce 1/200th of the energy consumed on it.

Beam Plus Plasma

However, let us try to salvage the idea. If ionization is the only factor which hinders the process, let us get rid of it! We can ionize the target nuclei. (Matter in this state is referred to as plasma.) So why not use plasma as the target for the accelerated nuclei?

There will be no ionization losses in a plasma. However, ionization is not the only way in which energy is lost. When a fast nucleus moves in a plasma, it loses energy due to elastic collisions with the charged particles, viz. the electrons and ions, constituting the plasma. The energy of the projectile nucleus will be transferred during these collisions to the plasma particles and will heat them. Once again, a calculation of the number of the collisions and the energy lost in them shows that the energy balance is negative. What else can we do? It turns out that something can indeed be done.

The particles in a beam will only lose energy during elastic collisions with plasma particles if their energy exceeds the energy of the plasma particles. If plasma is hot enough for the energy of its particles to be equal to the energy of the nuclei in the beam, there will be no energy loss due to elastic collisions. Usually, unprofitable energy losses occur in collisions between the beam particles and electrons. Hence it is sufficient to heat the electrons and leave the ions cold. This is quite a feasible idea. A beam of accelerated nuclei in combination with a plasma with hot electrons can indeed be used in a reactor with a positive energy balance. What is more, if we can produce a plasma in which the ions are also hot, we can even do without the beam! If the energy of the plasma particles is the same as that of beam particles, their collisions will also lead to nuclear reactions. All that remains to be done is to introduce appropriate materials into the plasma. Thus, we have arrived at the main idea for using fusion reactions to generate energy. The starting material must be in the form of a hot plasma so that the fusion reactions can take place on account of the thermal energy of the particles. This method of realizing fusion reactions is called thermonuclear fusion. It is these reactions occurring in the Sun that keep it in such a heated state.

What Temperature Do We Need?

In a body heated to a temperature T, the average kinetic energy of the particles is $mv^2/2 = 3/2(kT)$, where k is the Boltzmann constant, equal to 1.4×10^{-23} J/K. A rough estimate of the required temperature can be obtained as follows. We determine the temperature at which the thermal energy of the particles is 50 or 100 keV, the reaction cross-section being at maximum at this energy. It has been found that this temperature is 1.3×10^9 K, i.e. over a billion degrees! Fortunately, however, the energy of all the particles is by no means the same during random thermal motion. Particles heated to a temperature T have only an everage energy of $3/2(kT)$, and the energy of an individual particle may be more or less than this value. The high-energy particles make fusion reactions possible at an even lower temperatures, when the energy of most of the particles is quite small.

In order to calculate the rate of fusion reactions under these conditions, we must know how many particles have high energies and how many have low energies. The law of energy distribution of particles at a temperature T was derived in 1860 by the English scientist J.C. Maxwell.

The total number of reactions occurring per second can be calculated by summing

the contributions from particles of different energies. For the D + T and D + D reactions, the result of such a calculation is shown in Fig. 1.3. The product σv summed over all values of velocity and taking into

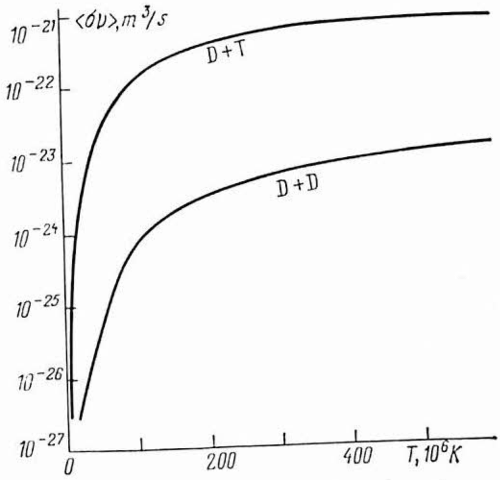


Fig. 1.3. Temperature dependence of the quantity $\langle \sigma v \rangle$, which determines the fusion reaction rate.

account the relative number of particles having such a velocity is enclosed within angle brackets and laid off along the vertical axis.

The quantity $\langle \sigma v \rangle$ averaged in accordance with Maxwell's distribution is very convenient in calculations. For example, the rate of a reaction can be determined by

multiplying this quantity by the densities n_1 and n_2 (the number of particles per cubic metre) of the starting materials. This gives the number of reactions per second per cubic metre: $S = n_1 n_2 \langle \sigma v \rangle$. The quantity $\langle \sigma v \rangle$ is shown in Fig. 1.3 as a function of temperature. The temperature is plotted in million kelvins. It can be seen that the reaction D + T has an appreciable rate only at a temperature of 50-100 MK.

The value of $\langle \sigma v \rangle$ for the D + D reaction is considerably smaller. It can be seen that the rate of this reaction remains much lower than for the D + T reaction even at higher temperatures. Still higher temperatures are required for the other reactions. The high temperatures are the main obstacle to the realization of controlled fusion. From this point of view, the D + T reaction has a clear advantage over all other reactions.

Thus, let us turn our attention to the D + T reaction and use it as an example to find the conditions under which a fusion reactor can be created.

A reactor can sustain itself and supply energy to external users only if the power gained from the fusion reaction exceeds the power losses. Energy may be lost, for example, due to inadequate thermal insulation of the material, which may be at a million degrees Kelvin. At such temperatures, the electrons will be stripped off from the atoms

and a plasma will be created. If the initial mixture contains $n/2$ deuterium atoms and $n/2$ tritium atoms per cubic metre, additional n electrons will appear after the formation of plasma, which will thus contain $2n$ particles per cubic metre. Let us now determine the energy required to heat such a plasma. For simplicity, we shall assume that the electrons, the deuterium nuclei, and the tritium nuclei all have the same temperature T. Under these conditions each particle has an average energy of $3/2(kT)$, which means that the $2n$ particles in a cubic metre will have an energy $E = 3/2(kT)\times 2n = 3kTn$.

We shall consider a reactor working at steady state (continuous operation). The energy losses in such a reactor are usually characterized by the time τ_E, i.e. how long in time the plasma energy can be confined for. The energy confinement time depends on the thermal insulation of the hot plasma from the cold walls of the reactor. The time can be determined from the following imaginary experiment. Suppose that we heat a plasma to a temperature T and then switch off the heating. The plasma begins to cool down due to imperfect thermal insulation, and loses energy at the rate of $3kTn/\tau_E$ per second.

For the continuous operation of a reactor, these losses must be compensated for. Partial compensation comes from the energy

liberated by the fusion reactions occurring in the reactor. The energy liberated in the reaction $D + T \rightarrow {}^4He + n + 17.6$ MeV is divided as follows between the reaction products: 3.5 MeV is imparted to the ^{4}He nucleus, while the remaining energy (14.1 MeV) is carried away by the neutron. If the size and density of the plasma are large, the energy imparted to the ^{4}He nucleus can be completely transferred to the plasma particles. The ^{4}He nucleus must then collide a large number with the plasma particles before reaching the reactor walls. However, plasma is practically transparent to neutrons which will take all their energy to the reactor walls. A special absorber can be set up at the reactor walls so that the energy of the neutrons can be liberated in the form of heat. This heat can then be converted into electrical energy, part of which can be utilized to heat the plasma.

Suppose that this can be done with an efficiency η. Estimates indicate that the efficiency of such a multi-stage process can scarcely exceed 30%. Thus, we shall assume that an energy $E = E_{ch} + \eta E_n$ can be returned to the plasma, E_{ch} being the energy liberated during the fusion reaction in the form of the energy of the charged particles, and E_n is the energy imparted to the neutron.

Let us now try to compile the heat balance for the plasma in a reactor with

a positive energy output. Since the density of the D and T nuclei in our reactor is equal to $n/2$, the number of fusion reactions taking place per second per one cubic metre of the plasma will be $\langle \sigma v \rangle n^2/4$. The amount of energy returning to the plasma after each reaction is equal to $E_{\mathrm{ch}} + \eta E_{\mathrm{n}}$. Thus the amount of energy liberated in the plasma will be $(E_{\mathrm{ch}} + \eta E_{\mathrm{n}}) \langle \sigma v \rangle n^2/4$, and this must be more than or equal to the energy losses $3kTn/\tau_E$. Thus, the energy balance relation will be $(E_{\mathrm{ch}} + \eta E_{\mathrm{n}}) \langle \sigma v \rangle n^2/4 \geqslant 3kTn/\tau_E$. Hence the following condition must be satisfied in order to ensure the successful operation of a fusion reactor:

$$n\tau_E \geqslant \frac{12kT}{(E_{\mathrm{ch}} + \eta E_{\mathrm{n}}) \langle \sigma v \rangle}.$$

For the T + D reaction, the right-hand side of this inequality has a minimum at a temperature $T = 10^8$ K. For $\langle \sigma v \rangle = 10^{-22}$ m^3/s, $E_{\mathrm{ch}} = 3.5$ MeV, $E_{\mathrm{n}} = 14.1$ MeV, and $\eta = 30\%$, we get $n\tau_E \geqslant 2 \times 10^{20}$ s/m^3. This is called Lawson's criterion after the English physicist who first derived it.

For the D + D reaction, the value of both E and $\langle \sigma v \rangle$ is much smaller than for the D + T reaction. Hence at a temperature of 4×10^8 K, Lawson's criterion is much more difficult to satisfy for the D + D reaction than it is for the D + T reaction: $n\tau_E \geqslant 5 \times 10^{22}$ s/m^3.

In order to get some idea of what these figures mean, let us do an imaginary experiment. We take a mixture of deuterium and tritium with the same density as atmospheric air, i.e. $n = 2 \times 10^{25}$ m^{-3}. It follows from Lawson's criterion that for the D + T reaction ($n\tau_E \geqslant 2 \times 10^{20}$ s/m^3) the energy confinement time τ_E in the reactor must be larger than 10^{-5} s. At first glance, this does not seem to be much. But for such a density (2×10^{25} m^{-3}) and temperature (10^8 K), the pressure in the mixture will be a few hundred thousand atmospheres. Confining matter heated to a hundred million degrees Kelvin at such a pressure even for a few millionths of a second is very difficult. The operation of a reactor under such conditions will be like a mighty explosion!

We can also proceed in another way. We reduce the density, say, to 2×10^{20} m^{-3}. The pressure of the plasma will then be about 1 atm, but the confinement time will be increased to about 1 s.

Thus, we can choose different parameters with which to operate a reactor if only ... . If only we can solve the main problem, i.e. how to confine matter at a temperature of 10^8 K. Even the most refractory material known to man cannot withstand a temperature of 10^5 K. Moreover, matter at such a high temperature is in the state of plasma and hence we must heat and confine plasma in order to attain thermonuclear fusion.

What Is Plasma?

As a matter of fact, scientists were quite familiar with the concept of plasma when the fusion reactions were first studied. The idea of plasma was introduced in 1923 by the American scientist I. Langmuir during his investigations of electric discharges in gases. During an electric discharge, a gas turns into a plasma.

It is worth mentioning that the investigation of electric discharges in gases has played a significant role in modern physics. Many fundamental discoveries, like the discovery of the electron, X-rays, and isotopes, were made during such investigations.

In spite of this, little attention was paid to plasma research until the 1950s. Nuclear fusion has pushed plasma physics to the forefront of science and made it one of the most important subjects of present-day research in physics. Thousands of scientists all over the world now work on plasmas and almost all universities and large research institutes have plasma physics laboratories. However, precious little was known about the properties of plasma in the early 1950s, although the properties which helped outline the basic trends towards the solution of the problem of controlled thermonuclear fusion were already known.

The main feature distinguishing a plasma from an ordinary gas is that it consists of charged particles, viz. electrons and ions. It is well known that the motion of charged particles can be controlled using electric and magnetic fields.

How a Charged Particle Is Affected by an Electric Field

If a charged particle is placed in an electric field, it will be acted upon by a force proportional to the charge. For a positively charged particle (ion), this force is directed along the electric field, while for a negatively charged particle (electron), the force acts in the opposite direction. The force accelerates the particle. Hence if a mixture of positively and negatively charged particles (plasma) is placed in an electric field, particles with different signs will fly in opposite directions, and a current will flow through the plasma.

...and by a Magnetic Field

Things are a lot more complicated in a magnetic field. The (Lorentz) force acting on a moving charged particle in a magnetic field is directed at right angles both to the magnetic field and to the particle's velocity. Hence the motion of the particle also depends on the direction of its velocity rela-

tive to the magnetic field. If the particle moves along the magnetic field, the latter will have no effect on it at all. However, if the particle velocity is at right angles to the magnetic field, the Lorentz force will

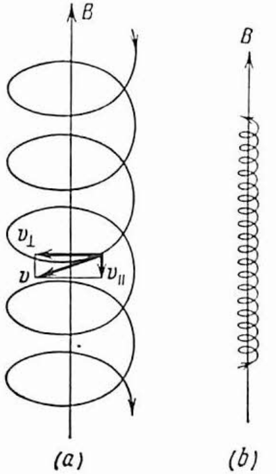


Fig. 1.4. Helical trajectories of charged particles in a uniform magnetic field: (*a*) ion trajectory and (*b*) electron trajectory.

make the particle move in a circle. In general, when the velocity direction is at an angle to the magnetic field, the particle will follow a helical path, i.e. it will move in a circle and at the same time move along the field (Fig. 1.4). The radius of this circle will depend on the magnetic induc-

tion B, the particle mass m, its charge q, and the component $v_\perp$ of its velocity: $r = mv_\perp/qB$.

The circular motion of charged particles in a magnetic field was first observed in 1895 by the English scientist J. Larmor. Hence it is called Larmor precession and the radius of the circle is called Larmor radius. The precession of charged particles in a magnetic field is the basic principle of particle accelerators, viz. cyclotrons. A particle in a cyclotron is accelerated by an electric field. The frequency of the precession $\omega = v/r = qB/m$ is independent of the particle's velocity. This happy coincidence considerably simplifies the control of cyclotrons. The quantity qB/m is called the cyclotron frequency.

A particle moves in a circle if the magnetic induction is the same (if the field is uniform) everywhere within the orbit and if the particle is not acted upon by any force other than the Lorentz force. If the magnetic field is not uniform, the Larmor radius will change during the motion of the particle and its trajectory will no longer be circular. Suppose, for example, that the magnetic induction is directed away from us (Fig. 1.5) and increases from right to left. Then the Larmor radius to the right of the centre will be larger than it is to the left. Consequently, the circle will not be closed and the particle will move

upwards during each rotation. This gradual displacement of the particle is called drift. Since positive and negative particles revolve in opposite directions, the drift of electrons will be opposite to that of ions. In our example, positively charged particles will drift upwards while electrons will drift downwards.

Drift is also observed in a uniform field if an electric field is applied at right angles to the magnetic field. In this case, the Larmor radius is changed because the work of electric forces will increase the

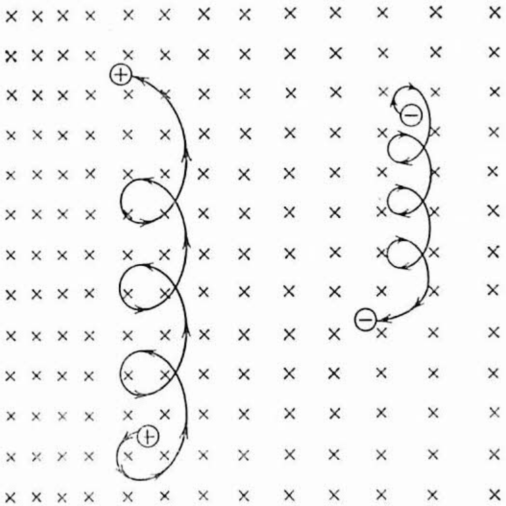


Fig. 1.5. Drift of charged particles in a nonuniform magnetic field.

particle's velocity over some of the trajectory, and decrease it elsewhere. For example, suppose that the magnetic field is directed away from us and the electric field is applied along the vertical upwards (Fig. 1.6). Then the velocity of a positively charged particle in the upper half of the trajectory will be higher than in the lower half. The Larmor radius will also change and hence the particle will drift to the left. By contrast, a negatively charged particle will move faster in the lower part of the trajec-

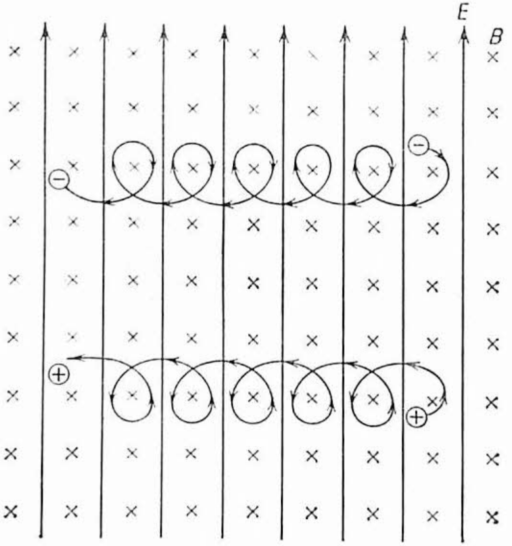


Fig. 1.6. Drift of charged particles in crossed electric nd magnetic fields.

tory. Since the negatively charged particle revolves in the opposite direction, the direction of its drift is the same as that of a positively charged particle. Thus, in crossed electric and magnetic fields, all the particles (ions as well as electrons) drift in the same direction.

Collective Motion of Plasma Particles

Thus the motion of charged particles can be quite complicated. But there is more to this topic than meets the eye. Individual charged particles cannot be called a plasma. A plasma begins with the collective motion of particles. As a result of the Coulomb interaction of charged particles, the motion of each charged particle influences the motion of all the other particles. The collective properties of plasma are primarily manifested in its quasineutrality (quasi means "as if"). Although a plasma consists of charged particles, the number of negative particles in it is usually equal to the number of positive particles and a plasma is electrically neutral on the whole. The quasineutrality of plasma is observed to a very high degree of accuracy. If quasineutrality is violated accidentally at some place, say, if some electrons move, thus creating an excess of ions in one place and an excess of electrons in another, a strong electric field is produced in the plasma and

the electrons return quickly to their original sites. In a hot plasma, quasineutrality is violated now and then due to the thermal motion of particles, but is restored forthwith. Since electrons are much lighter than ions, the violation and restoration of the equality of electronic and ionic number densities occurs mainly through the motion of electrons which oscillate rapidly about nearly stationary ions. These oscillations are so characteristic of a plasma that they are called plasma oscillations or Langmuir oscillations after the scientist who discovered them. Langmuir obtained the formula $\omega = 56 \sqrt{n}\ s^{-1}$ for the frequency of these oscillations, which is called the Langmuir frequency. In addition to the Langmuir frequency, oscillations with many other frequencies are also possible in plasma. For example, acoustic waves can propagate through a plasma as they do through any other gas. In a magnetic field, a whole range of waves may propagate through a plasma.

Besides this variety of oscillations, collective motions of a plasma can also occur in the form of flows similar to the flow of gases or liquids. This is accompanied by the creation of intrinsic electric and magnetic fields in the plasma, which together with the external electric and magnetic fields in turn influence the motion of the plasma. It is these collective properties of a plasma that make it so difficult to control.

The Idea of Magnetic Confinement

We are now in a position to understand how a hot plasma can be confined by a magnetic field. At a temperature of 10^8 K which has to be produced in a fusion reactor, deuterium ions have a velocity of about 10^6 m/s, while the velocity of the electrons will be about 6×10^7 m/s. If these particles are subjected to a magnetic field of induction 1 T, the Larmor radius for deuterium ions will be about 2 cm, while that for electrons will be 0.03 cm. Hence the magnetic field helps confine the motion of individual particles within these limits and thus isolates them from the reactor walls.

The technology of the confinement of individual particles using a magnetic field was developed for particle accelerators. In modern accelerators, particles can be confined in the magnetic field of a synchrophasotron for many million cycles. Hence, if we were to deal only with the confinement of individual charged particles, a fusion reactor could be constructed quite easily. However, we are dealing with a plasma and this considerably complicates the problem.

The charged particles constituting a plasma create their own magnetic field while revolving in an external magnetic field. The field of the charged particles is directed against the applied field. Hence when

a plasma is placed in a magnetic field, the magnetic induction in the region occupied by the plasma decreases. This phenomenon is called diamagnetism. Diamagnetism can also be explained in a different way. The motion of a charged particle in a circle is

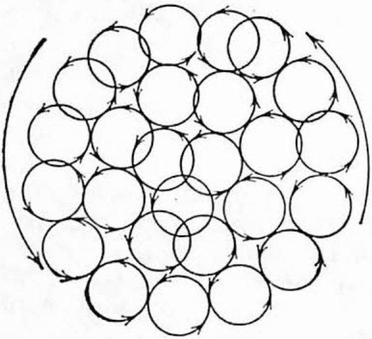


Fig. 1.7. Emergence of diamagnetic current during plasma confinement in a magnetic field.

equivalent to an electric current flowing in this circle. Inside a plasma, the currents from adjacent particles compensate one another. At the plasma boundary, however, there is no compensation (Fig. 1.7). As a result, an electric current flows across the surface of the plasma. The magnetic field produced by this current decreases the external magnetic field in the volume occupied by the plasma. The diamagnetic

current increases with plasma temperature and density. As a result, the magnetic field inside the plasma decreases. The diamagnetic current reaches its highest value when the magnetic field inside the plasma completely vanishes. After this, an increase in the plasma density and temperature no longer causes an increase in the diamagnetic current.

Like any current-carrying conductor in a magnetic field, the plasma is acted upon by a force. Since a diamagnetic current flows across the plasma surface, this force is applied to the surface and is directed from the external magnetic field into the plasma where the magnetic field is weaker. Thus we can say that the magnetic field exerts a pressure on the plasma surface. This pressure can be used to confine the plasma within a magnetic field. The pressure is at a maximum for the maximum diamagnetic current when the field inside the plasma is zero. If the induction of the external magnetic field is B, the pressure exerted by the field on the plasma surface will be $P_B = \frac{10^7}{8\pi} B^2$.

If the diamagnetism of the plasma is not strong enough to expel the field completely so that the residual magnetic field in the plasma has an induction B_1, the pressure will be determined by the difference between the pressures of the magnetic fields on

the opposite sides of the plasma:

$$P_B = \frac{10^7}{8\pi}(B^2 - B_1^2).$$

Like an ordinary gas, the plasma has a pressure equal to nkT. Thus the plasma is subjected to the pressure P_B of the external magnetic field on one side and to the sum of the pressures of the plasma and the magnetic field inside the plasma, viz. $nkT + \frac{10^7}{8\pi} B_1^2$ on the other side. If these pressures are equal, the plasma boundary will be in equilibrium:

$$nkT + \frac{10^7}{8\pi} B_1^2 = \frac{10^7}{8\pi} B^2.$$

This formula reflects the basic idea of the magnetic confinement of plasma. Obviously, the ratio of the pressure of the plasma to the pressure of the magnetic field is important in magnetic confinement. This quantity is denoted by the Greek letter β:

$$\beta = \frac{8\pi nkT}{10^7 B^2}.$$

By dividing this relation by $\frac{10^7}{8\pi} B^2$, we can write the equation for the equilibrium of plasma in a magnetic field in the following form:

$$\beta + \frac{B_1^2}{B^2} = 1 \quad \text{or} \quad \beta = 1 - \frac{B_1^2}{B^2}.$$

From the point of view of economy of operation of a fusion reactor, it is desirable to make β as large as possible. This would reduce the losses incurred in creating a powerful magnetic field to a minimum. However, the larger the value of β, the more difficult it is to confine plasma since the plasma motion, when the plasma pressure becomes comparable to the pressure of the magnetic field, considerably affects the structure of the magnetic field; as a rule, the effect on the field structure is adverse. The confinement of a plasma by a magnetic field is possible if $\beta < 1$. Otherwise, the plasma pressure exceeds the pressure of the magnetic field and the plasma cannot be confined.

What is the magnitude of the magnetic field pressure? The pressure depends on the magnetic induction B and, at present, magnetic fields with induction up to 200 T have been obtained in the laboratory, although such fields have been produced just for a few millionths of a second and the equipment producing the field is usually destroyed. Obviously, it is impossible to construct a continuous fusion reactor under such conditions. Magnetic inductions up to 25 T can be produced at present under stationary working conditions. These magnets are made of superconductors, and hence the magnetic field, once produced, can be preserved for an indefinitely long time. The

only drawback of these magnets is that they have to be cooled down to temperatures of about 20 K, which is quite expensive. Moreover, superconductivity is destroyed at $B \simeq 12$ T and hence the magnetic induction must be lower than this critical value everywhere. In the real equipment for magnetic confinement of plasma, it has been found that the magnetic induction in the volume occupied by the plasma is usually lower than in the coil producing the magnetic field. Hence the magnetic induction that can be used for confining plasma is somewhere around 5 T.

A magnetic field with such an induction creates a pressure of $P_B = \frac{10^7}{8\pi} \times 25 = 10^7$ Pa (i.e. about 100 atm). This means that a plasma with a greater pressure cannot be confined by such a magnetic field. At a temperature of 10^8 K, a pressure of 10^7 Pa is generated by a plasma with a density of 6×10^{21} m^{-3}. Since a plasma consists of electrons and ions, this means that one cubic metre must not contain more than 3×10^{21} electrons and 3×10^{21} ions.

According to Lawson's criterion, $n\tau_E \geqslant 2 \times 10^{20}$ s/m^3 and, for a fusion reactor to be advantageous from the energy point of view, the confinement time should be equal to or greater than 0.1 s (for an ionic density of 3×10^{21} m^{-3}).

Considering that for $\beta \simeq 1$ plasma confine-

ment is very difficult to implement, we should take $\beta \simeq 0.1$, to be on the safe side. Then the ionic density of the plasma in a reactor with magnetic confinement will be 3×10^{20} m^{-3} and hence the confinement time must be about 1 s. Let us recall that Lawson's criterion deals not just with the confinement time for the plasma but rather with the time during which the energy must be confined within the plasma. Naturally, if we cannot confine the plasma, it will move towards the wall together with its energy. Hence the energy confinement time must be smaller than the time the plasma can be confined, indeed it may be much smaller. This is because of heat conduction. In a piece of copper, for example, atoms are held at lattice sites. However, if a rod of copper is heated and one of its ends is then immersed in cold water, the entire rod is rapidly cooled. The cooling time depends on the size of the body, its thermal conductivity, density, and heat capacity. The thermal conductivity $\varkappa$, density ρ and heat capacity C always appear in heat transfer formulas as the group $\varkappa/\rho C$, and it is therefore convenient to use this group, called the heat transfer coefficient $\chi = \varkappa/\rho C$ m^2/s, for calculations. If the heat transfer coefficient is known, the cooling time of a body of size a can be calculated from the formula $\tau_E \simeq a^2/4\chi$.

Heat transfer by conduction takes place

as the result of collisions between the particles constituting the body. Hence the heat transfer coefficient depends on the displacement l of individual particles and the time τ between collisions: $\chi = l^2/\tau$. In solids like copper, l is the amplitude of atomic oscillations, while for gases l is the mean free path of the molecules. In the absence of a magnetic field, heat transfer in a plasma takes place in nearly the same way as in a gas. The mean free path of the particles depends on the temperature and density of the plasma: $l = 3 \times 10^8\ T^2/n$. In a fusion reactor ($n \simeq 3 \times 10^{20}\ \mathrm{m}^{-3}$, $T \simeq 10^8$ K), the mean free path is very large, i.e. $l \simeq 9 \times 10^3$ m. The time between ion collisions under these conditions is $\tau \simeq 6 \times 10^{-3}$ s. Hence the heat transfer coefficient in a thermonuclear plasma is large, i.e. $\chi \simeq 10^{10}\ \mathrm{m}^2/\mathrm{s}$. Correspondingly, the heat transfer time is very small. Given such a heat transfer coefficient, it would be impossible to satisfy Lawson's criterion. Even for a reactor with a 1-km long plasma, the heat confinement time would be just about $\tau_E \simeq 2 \times 10^{-5}$ s. Hence the thermal conductivity of the plasma must be reduced. Fortunately, we do not have to look very far, as the magnetic field itself again provides a solution to the problem. In a magnetic field, the plasma particles move in circular trajectories, and hence in each collision heat is not transferred over the mean free

path, which runs to several thousand metres, but over the radius of the circle, which is of the order of one centimetre for ions in a plasma. Hence the heat transfer coefficient for a plasma in a magnetic field is several times smaller than it is in the absence of a magnetic field. The coefficient can be calculated from the formula $\chi = 2 \times 10^{-18}\ n/B^2\sqrt{T}$. For a plasma with a density $n \simeq 3 \times 10^{20}\ \mathrm{m}^{-3}$ and a temperature $T \simeq 10^8$ K, we obtain $\chi \simeq 6 \times 10^{-2}\ \mathrm{m^2/s}$ even for $B = 1$ T. For such a heat transfer coefficient, the required confinement time $\tau_E \simeq 1$ s can be obtained in a reactor the size of whose plasma is just 1 m. Hence the problem of heat conduction can be tackled with the help of a magnetic field. True, the fall in thermal conductivity of the plasma in a magnetic field only occurs perpendicular to the magnetic field, while in the direction of the magnetic field, heat transfer is as rapid as before. This fact must always be borne in mind while designing a reactor.

Magnetic confinement was thought of independently in this form by scientists in the USA and the USSR in 1950. The estimates contained in these first papers created the impression that it would not be difficult to attain prolonged plasma confinement using a magnetic field or to suppress its thermal conductivity to a sufficiently low value. Hence fusion investigations were started in an atmosphere of general optimism.

Chapter 2
Pinching Discharges

Let Plasma Confine Itself!

The simplest way to produce a magnetic field that will confine a plasma is to use an electric current flowing straight through the plasma. In this case, the magnetic field lines will be circular in shape, embracing the plasma column. If the plasma column is placed in a tube, the motion of the plasma particles along the field will be immaterial and the plasma particles will have to cross the magnetic field in order to reach the walls of the tube. This means that the magnetic field isolates the plasma from the walls. This is just what we need! Moreover, since a plasma has considerable electric resistance, the current flowing through the plasma will heat it in the same way as it heats, say, the filament of a lamp. The stronger the current, the more the plasma is heated. At the same time, the pressure of the magnetic field confining the plasma also increases. At a certain large current, the magnetic field's pressure may exceed the plasma pressure and the column will shrink. The "pinching" heats the plasma even more strongly.

Thus we obtain quite a rosy picture: the plasma heats itself and confines itself! This remarkable idea originated simultaneously at the beginning of the 1950s on both sides of the Atlantic and aroused great enthusiasm among scientists. Simple calculations showed that the plasma could be heated to the fusion temperatures of 100 million degrees K using a current of about one million amperes. This triggered a flurry of activity. Over a short span of a couple of years, devices capable of passing a current of 100-200 kA through a plasma were created. This limit was further raised to 2-4 million amperes.

At that time, many of the instruments that are now used for plasma studies had not been designed. The experimental physicists had only the simplest instruments to measure current and magnetic induction. The only instrument available to observe the plasma itself was a movie camera, although the plasma (at least, the plasma the scientists were striving to create) should have been invisible. After all, the discharge was to be passed through deuterium and the single electron is stripped away from the nucleus to form the plasma. This leaves bare deuterium nuclei, which cannot emit radiation in the visible range. Deuterium plasma only emits radiation in the form of X-rays. In spite of this, even the earliest experiments showed that, contrary to expectations, the

plasma glowed brightly in the visible region. Hence photographic and spectral methods were widely used in subsequent experiments on plasma studies. Of course, neutron counters were also installed near the unit to record the fusion reactions occurring in the plasma, should the conditions necessary for this be fulfilled.

The experiment proper was carried out as follows. A glass or ceramic tube with metal electrodes at both ends was evacuated to a high vacuum and filled with hydrogen or, if the scientists were striving to create the conditions suitable for a fusion reaction, with deuterium. A large bank of capacitors was charged to a voltage of several thousand, or sometimes even to a hundred thousand, volts. When the capacitors were connected to the metal electrodes, a noise like thunder was heard. At the same time, a discharge accompanied by a blinding light took place in the tube. The first success came soon after the beginning of the experiments.

Here Comes the Compression!

In order to observe the behaviour of the plasma, a high-speed movie camera capable of taking two million shots per second was used. A sequence of frames shot during an experiment is shown in Fig. 2.1. It can be seen that the plasma begins to glow brighter

and brighter as the discharge develops. The region of glow tears away from the walls and begins to shrink. It becomes narrower and narrower, and then begins to increase again.

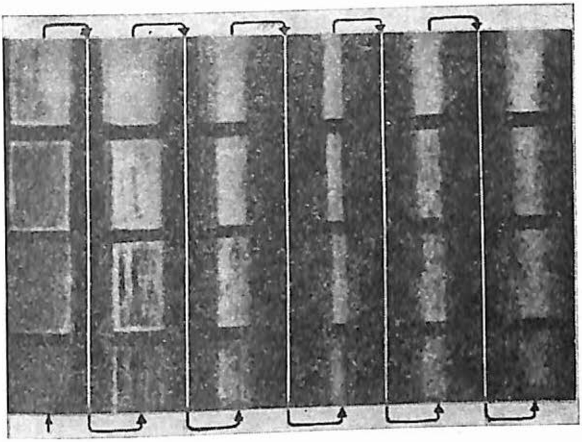


Fig. 2.1. Stills from a high-speed photograph sequence of a discharge. Arrows show the sequence of frames.

The minimum diameter of the plasma column is about one tenth of its value at the beginning of the discharge, when the plasma fills nearly the whole of the vacuum tube.

And the Neutrons!

At the instant of maximum compression of the plasma, a neutron detector mounted near the unit registered a neutron pulse. This meant that fusion reactions were taking place in the discharge!

Neutrons were first obtained in a pinching discharge in 1952 by the Soviet physicists N.V. Filippov and V.I. Sinitsyn at the Kurchatov Institute of Atomic Energy. However, physicists are sceptics by nature and there were doubts as to whether these neutrons were the neutrons and whether fusion conditions had indeed been attained in the plasma.

In order to verify this, the energy of the neutrons was measured. If the neutrons were produced in the fusion reaction $D + D \rightarrow {}^3He + n$, their energy must be close to 2.4 MeV.

The measured values were quite unexpected: the energies of the neutrons leaving the discharge in the direction of the current flowing through the plasma were found to be higher than 2.4 MeV. The energies of the neutrons leaving in the opposite direction were found to be less than 2.4 MeV. This means that the reacting deuterium ions were moving faster in the direction of the electric current. This was very unfortunate since it meant that the reactions in which the neutrons were being produced could not

be fusion reactions for fusion reactions would have to take place as a result of the thermal motion of particles and hence there should be no preferred velocity.

The fact that accelerated deuterium ions are indeed produced in the discharge was verified by measuring the energy of the ions released during a discharge. A small hole was made in an electrode or the side wall of the discharge tube. The ions emerging from the hole were analyzed by a mass spectrometer. It was found that particles with energies of several hundred thousand electronvolts were somehow being produced in the discharge, although the voltage across the electrodes of the discharge tube was much lower. It became clear that the neutrons were being produced as a result of the fusion reactions involving these accelerated ions.

But what mechanism was accelerating ions to such high energies? This was just one of the many questions that were raised after the first experiments on pinching discharges. Together with the neutron pulse, a powerful pulse of X-rays was also emitted. What is the origin of this pulse and why does the plasma glow so brightly?

The spectrum of the glow was investigated. It was found that the light emitted by the plasma contains emission lines of oxygen, carbon, and silicon. How do such lines appear in a hydrogen plasma? On the whole, the plasma acts quite strangely.

When the pinching discharge experiments were just starting, physicists had an idyllic picture of a plasma column compressed by a magnetic field, with the electric current flowing along this column and creating the magnetic field. The situation was assumed to be stationary. The behaviour of plasmas in actual experiments was found to be quite different. Let us look at the frames in Fig. 2.1. The column is compressed and then expands, is compressed again, and so on. All this happens in a few millionths of a second! This is hardly what we would expect in a stationary process.

Here, at last, was something to puzzle the theoretical physicists!

However, they quickly solved the riddle. It was found that balancing the plasma pressure by the pressure of the magnetic field is not sufficient to confine a plasma. The equilibrium must be stable as well.

This means that if there is a random deviation in the plasma boundary from the equilibrium position, a force tending to return it to equilibrium must arise. Otherwise the whole procedure becomes meaningless. If the force that arises causes an even larger deviation from the equilibrium position, the plasma continues to expand until it touches the walls of the discharge tube and is quenched. The theorists immediately came up with a name for this rather undesirable process: they termed it plasma instability.

This term, which appeared in the lexicon of plasma physicists at the beginning of the 1950s unfortunately became unavoidable in all discussions dealing with plasma confinement. Literally dozens of different types of plasma instability have been discovered theoretically, and so far nobody has come up with a design of plasma confining unit which does not suffer from instability.

In the first experiments on pinching discharges, the plasma behaviour was determined by a sausage-like instability, which was first examined by the Soviet scientist B. A. Trubnikov. He explained it in terms of the following mechanism. At some point in time, the thickness of the plasma column at some place will be less than it is elsewhere in the vicinity. The magnetic field of the current is inversely proportional to the radius r of the plasma column: $B = 2 \times 10^7 \, I/r$. Hence the magnetic field at the point with the smaller r will be larger than elsewhere in the neighbourhood, and thus the pressure exerted by the field on the plasma also increases (Fig. 2.2). The plasma begins to flow into the neighbouring regions and hence the radius of the column falls still further at this point. The magnetic field becomes even stronger and compresses the column even more, and so on. In a few microseconds, the constriction completely cuts the plasma column.

Due to self-induction, a strong electric field is produced in the region of the constriction and the deuterium ions and electrons are accelerated in this field to energies of several hundred thousand electron-volts. This explains the neutron and X-ray

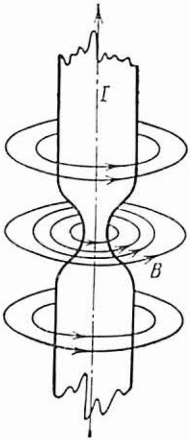


Fig. 2.2. Sausage-like instability. The plasma column is disrupted by increased magnetic field pressure in the region of constriction.

pulses at the instant of maximum compression of the plasma. As the current decreases, the magnetic field produced by it falls and the plasma swiftly expands since there is no force to confine it. When the plasma touches the walls of the vacuum tube, the surface layer of the wall vaporizes and

atoms of silicon, oxygen, carbon, and the other elements in the surface material enter the plasma. These atoms produce the bright glow of the plasma. More and more impurities appear in the plasma at each pulse.

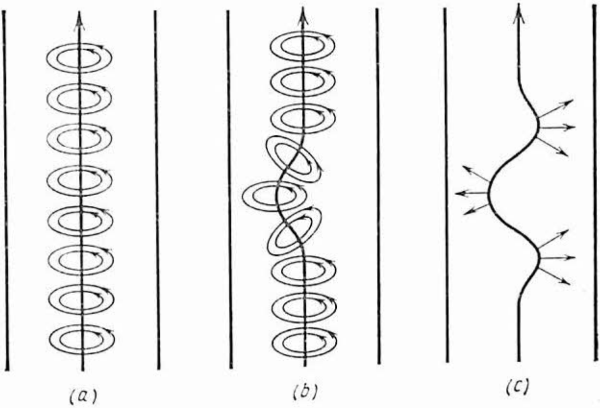


Fig. 2.3. Kink instability. A kink (*b*) appearing in a straight current-carrying plasma column (*a*) produces an excess magnetic field tending to make the kink more severe (*c*).

Another type of instability, viz. the kink instability (Fig. 2.3), also appears in the plasma through a similar mechanism. If a small kink appears in the plasma column, the magnetic field on the inner side of the kink increases, and so does the magnetic pressure. As a result, the column bends even more sharply until it breaks or touches

the wall. All this takes place quite rapidly, in a matter of a few microseconds, since the plasma is so light and the forces acting on it are so strong. The theory of plasma compression in a column with a high current was developed by the Soviet scientists M.A. Leontovich and S.M. Osovets in 1953. They calculated the pulse frequency and velocity for the pinching discharge and even determined the instant when the neutron pulse was emitted. The results of their theoretical investigations were found to be in good agreement with the experimental results. This in itself was a remarkable achievement. The analysis of pinching discharges was a big step towards an understanding of plasma physics. However, the results were still miles away from what was required in order to attain the cherished goal of controlled fusion. Even in the strongest discharges at the instant of the maximum compression, a temperature of about one million degrees Kelvin was attained in the plasma having a density $n = 10^{23}\ \mathrm{m}^{-3}$. The plasma remained in this state for a period of time $\tau = 10^{-7}$ s. This means that the energy confinement time did not exceed this value and hence the product $n\tau$ in these experiments was $\leqslant 10^{16}\ \mathrm{s/m}^3$ instead of the cherished goal $n\tau = 2 \times 10^{20}\ \mathrm{s/m}^3$.

Theta Pinch

Another type of discharge, called theta pinch by American physicists, was also investigated. The term "pinch" was first proposed in 1937 by the American physicist

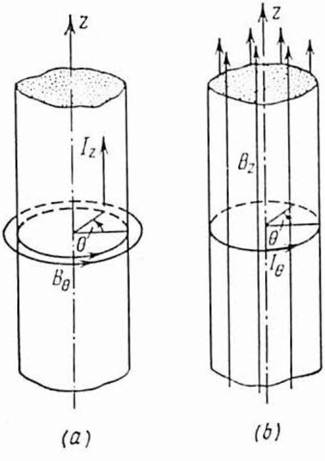


Fig. 2.4. (*a*) Linear pinch effect and (*b*) the compression of a cylindrical plasma column by an external longitudinal field.

L. Tonks for a discharge which contracts under its intrinsic magnetic field. The expression "theta pinch" owes its origin to the configuration pattern of the current and the magnetic field in the discharge in cylindrical coordinates z, θ, r (Fig. 2.4). In an ordi-

nary linear discharge, which was discussed in the previous section, the current flows along the z-axis of the plasma column, while the magnetic field produced by this current was directed along a circle over which the angle θ was measured (Fig. 2.4*a*). Alternatively, we can pass the current through a circle in the direction of the angle θ and the magnetic field produced by the current will then be directed along the z-axis (Fig. 2.4*b*). In order to distinguish between these two versions, the Americans introduced the terms "zeta pinch" and "theta pinch", respectively.

While a plasma current could be produced in a direct discharge by simply applying a high voltage across the electrodes, magnetic induction is used to produce a current in a theta pinch setup. The discharge tube is placed in a one-loop coil formed by bending a thick copper bar. When a bank of capacitors charged to a very high voltage is discharged through this coil, a magnetic field is produced in the coil in a few microseconds. This sharp change in the magnetic field induces an electric field in accordance with the laws of electromagnetic induction. It is this electric field that produces a strong circular current. The subsequent course of events in a theta pinch is more or less the same as in an ordinary linear discharge. The plasma is compressed by the magnetic field of the current into a dense ring-sha-

ped cluster. The temperature increases rapidly and neutrons appear during powerful discharges. To begin with, the Americans believed that theta pinch does not suffer from the instabilities inherent in ordinary linear discharges. The hopes arose because the yields of neutrons in the powerful Scylla and Scylla-1 units were much higher than yields from linear discharges and they reached 10^8 neutrons per pulse. Howe-ver, subsequent investigations showed that theta pinch discharges were not devoid of instability. This can be seen clearly from photographs obtained by a group led by the Soviet scientist I. F. Kvartskhava at the Sukhumi Physico-Technica lInstitute. Similar photographs were later obtained at other laboratories. The photographs were taken through the end of the tube along the coil axis (Fig. 2.5). These photographs show that the plasma ring formed at the beginning of the discharge started shrinking rapidly. The shape of the ring then became irregular until it looked like a gear. The teeth of the gear started protruding and soon reached the walls of the vacuum chamber. The shape of the plasma became more and more disordered and asymmetric. A plasma glow appeared near the surface of the vacuum chamber and the discharge was extinguished. This behaviour can be understood by examining the magnetic field's configuration in a theta pinch

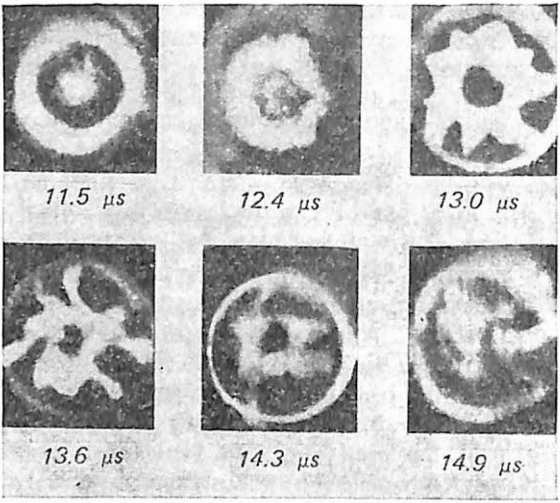


Fig. 2.5. Stills showing the growth of a theta pinch instability.

(Fig. 2.6). The magnetic induction lines embrace the current flowing in the plasma ring in exactly the same way as in a linear discharge. Hence the same types of instability can appear in a theta pinch as in an ordinary pinch. The "teeth" shown in Kvartskhava's pictures are formed due to the sausage-type instability. As in the case of a linear pinch, strong electric fields appear in these places and the plasma ions are accelerated in them. These accelerated ions

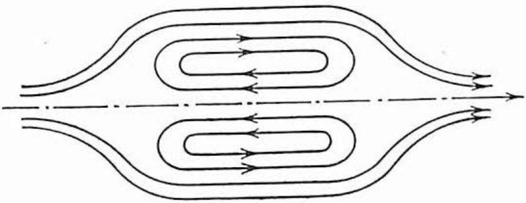


Fig. 2.6. Configuration of a theta pinch magnetic field in a contracting plasma.

trigger the reactions in which neutrons are generated.

The American physicists exhibited an enviable persistence in developing the theta pinch. Experiments were continued with different versions of the Scylla units for two decades up to the end of the 1970s. The sizes of the devices and the power input have increased continuously and, in spite of the drawbacks of the theta pinch, the scientists hoped to create conditions suitable for fusion reactions. They almost succeeded in their attempts! The latest version of the unit, called Scyllac, was 8 m long and had a tube bent in an arc of about 120°. It was proposed to complete the circle by adding two more segments in order to prevent the plasma losses at the ends of the tube. The plasma in the unit had a density of 2×10^{22} m^{-3} and the temperature of the ions, estimated from the neutron yield, was found to be about (2-3) $\times$ 10^7 K. However,

in spite of the imposing size of the unit, the plasma confinement time was not longer than 2×10^{-5} s. Hence the product $n\tau$ in these experiments did not exceed 4×10^{17} s/m^3. This small confinement time was due to instabilities. The struggle against these instabilities was very difficult and by the end of the 1970s, the Scyllac programme could no longer compete against other approaches to controlled thermonuclear fusion and was eventually discontinued. However, experiments with linear theta pinches that do not form a closed circle are still continuing. This is so because near-fusion temperatures are so easy to attain in these units: a rapid discharge from banks of capacitors does the trick! The main problem still to be addressed is to increase the plasma confinement time.

Plasma Focus

In the course of experimental investigations of the pinching discharge, the Soviet scientist N.V. Filippov discovered a design that has not only survived to this day, but even continues to be a possible way of obtaining controlled fusion. Filippov made his discovery at the beginning of the 1950s when investigations on pinching discharges were at their peak. When it was found that impurity radiation is a major cause for the loss of energy, Academician L.A. Artsimo-

vich suggested that the porcelain wall of the discharge chamber be replaced by copper. It was thought that the good thermal conductivity of copper would reduce the heating of the surface when it comes into contact with the plasma, and also reduce the flux of impurities entering the plasma. To reduce the risk of accidental electrocution, the copper side wall of the discharge tube was connected to the cathode. This led to the configuration shown in Fig. 2.7. When a high-voltage pulse was applied to the anode, there was an electric discharge in the chamber. The scientists were, however, amazed to note a strange effect, namely, that the replacement of the material forming the side wall had increased the neutron yield. Moreover, the neutron pulse in this type of a system was obtained consistently, i.e. in each shot, and not randomly as in an ordinary discharge. By installing lead collimators with small apertures and a neutron counter, Filippov was able to determine the source of these neutrons. They came from an astonishingly small region (a fraction of a centimetre) on the axis between the anode and the cathode. During each discharge in the unit, the plasma was pulled from all sides by the magnetic field into the centre of the system. The plasma fluxes collided at a point on the symmetry axis, and a dense plasma cluster was formed. This cluster served as the source of the neutrons.

This region, and subsequently the entire unit, was termed a "plasma focus" (see Fig. 2.7). A plasma jet is condensed to a

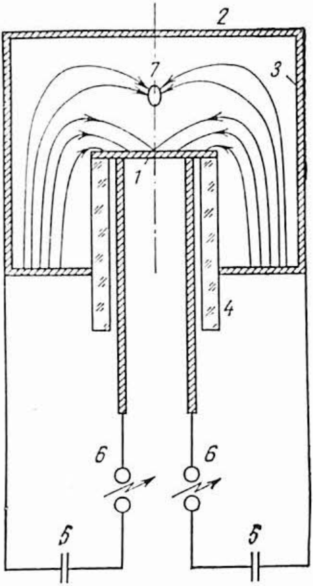


Fig. 2.7. Schematic diagram of a "plasma focus" unit: *1*) anode, *2*) cathode, *3*) side wall, *4*) insulator, *5*) bank of capacitors, *6*) discharger, *7*) plasma focus, viz. the region where the plasma cluster is formed.

point on the axis in the same way as a beam of light is focussed by a lens.

The processes which occur in a plasma focus discharge were very difficult indeed

to investigate. All the events take place very rapidly and in a very small region. The time is measured in billionths of a second.

Like an ordinary pinching discharge, a plasma focus discharge also suffers from instability and a flux of accelerated particles is formed. But the plasma density in this case is so high that the accelerated particles give away their energy to the plasma and heat it. If the power of the capacitors feeding the discharge is high enough, the temperature of the plasma at the plasma focus may rise to tens of millions of degrees Kelvin and even temperatures close to 100 million degrees Kelvin were reached in some experiments. Fusion reactions become common and the neutron flux reaches very high values: up to 10^{12} neutrons per pulse.

The plasma confinement time is the only factor hindering the use of the plasma focus technique for a fusion reactor. The energy confinement time in the plasma focus does not exceed 10^{-8}-10^{-7} s. The plasma density at this instant is about 10^{23}-10^{24} m^{-3}, and hence we obtain the product $n\tau \simeq 10^{16}$ s/m^3.

The plasma confinement time can be increased by increasing the power and energy of the voltage supply.

As the input energy increases, the neutron yield increases very rapidly. Hence it

is possible to use a plasma focus unit as a source of neutrons in a hybrid fusion reactor. Neutrons are used in such a reactor to cause the fission of uranium nuclei in a shell surrounding the plasma focus. We shall discuss the details of the process in Chap. 11.

Battlefield Map

To see how far we must go from the first experiments to a fusion reactor, we use a diagram in which the plasma temperature T is plotted along one axis and the product $n\tau$ of the plasma density and the confinement time along the other axis. The latter quantity determines the feasibility of a fusion reactor (Fig. 2.8).

The cherished region of controlled thermonuclear reactions $T \simeq 100$ million degrees K and $n\tau \simeq 2 \times 10^{20}$ s/m^3, lies in the upper right-hand corner of this diagram. The results of investigations of pinching discharges are shown in the bottom left-hand corner ($T \simeq 10^6$ K, $n\tau \simeq 10^{16}$ s/m^3). It is a long, long way to the "fortress of fusion": the temperature must be raised by a factor of 100 and the confinement time must be increased 10 000 times.

A very high temperature ($T \simeq 6 \times 10^7$ K) is reached at the plasma focus, but the plasma confinement times are quite modest ($n\tau \simeq 3 \times 10^{16}$ s/m^3). From the

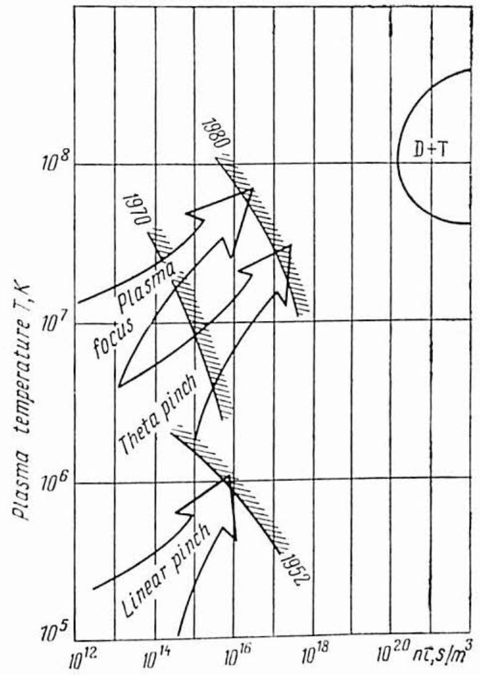


Fig. 2.8. Battlefield map.

highest achievements of the theta pinch ($T \simeq 3 \times 10^7$ K and $n\tau \simeq 2 \times 10^{17}$ s/m^3), it is likewise very far to the "fortress of fusion".

Although investigations of the pinching discharges did not lead directly to the conditions for nuclear fusion, they played

a very important role in the development of plasma physics. Several methods for studying plasmas were worked out during these experiments, and scientists came to a better understanding about the behaviour of plasmas and about their interactions with magnetic fields.

Chapter 3

Magnetic Traps

The plasma instabilities discovered during experiments on pinching discharges necessitated a search for other ways of confining plasmas using a magnetic field. In 1952, G.I. Budker in the USSR and, independently, H. York and R. Post in the USA, devised a trap in which the plasma confinement time could be prolonged by reflecting charged particles from regions with enhanced magnetic induction.

Figure 3.1 shows the simplest trap. It consists of two closely spaced coils for creating a magnetic field. The magnetic induction lines in the trap are like a bottle with two necks. Hence these confinement systems are often called magnetic bottles. The magnetic induction in the necks is higher than it is in the middle of the trap. This enhanced induction creates a magnetic "stopper" which prevents the plasma from leaving the trap. Hence Budker called his device a trap with "magnetic stoppers". The American scientists termed their trap "a system with magnetic mirrors". The operation of the trap can be described as follows. If a

particle has a velocity component $v_{\parallel}$ along the magnetic field and a component $v_{\perp}$ perpendicular to it, it will move in a circle of radius $r = mv_{\perp}/qB$ and move along the magnetic induction line with a velocity $v_{\parallel}$.

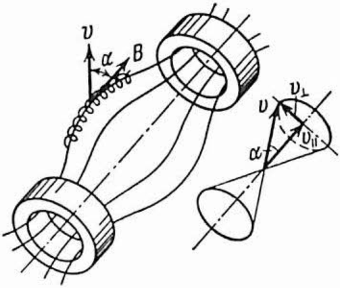


Fig. 3.1. Magnetic mirror trap. If the particle velocity in the middle of the trap forms a large angle with the direction of the magnetic field, the particle is reflected from magnetic mirrors and is confined in the trap. If the angle is too small, the particle falls into the "loss cone" and leaves the trap.

As a result, it has a helical trajectory. Near the mirrors, the magnetic induction increases and the lines of force become denser. It can be seen from Fig. 3.2 that the Lorentz force, which is always perpendicular to the line of force and to the particle velocity, acquires a component along the trap's axis which retards the particle. The longitudinal velocity of the particle begins to decrease. Of course, the total energy $W =$

$(mv_{\parallel}^2 + mv_{\perp}^2)/2$ is conserved because the decrease in the longitudinal velocity $v_{\parallel}$ is compensated for by an increase in $v_{\perp}$. The particle's angular velocity around the central axis increases and its displacement

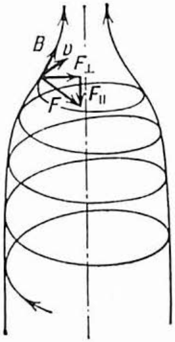


Fig. 3.2. As a particle approaches a mirror, the Lorentz force acquires the component $F_{\parallel}$, which hinders the motion of the particle along the axis and returns it to the centre of the trap.

along the axis gets smaller. This is manifested by a decrease in the lead of the helix. The helix starts to resemble a compressed spring. Finally the velocity $v_{\parallel}$ falls to zero and the particle then begins to move in the opposite direction, i.e. towards the centre of the trap.

The redistribution of energy between the longitudinal and transverse motions when a particle is reflected takes place in such a way that the ratio of the transverse energy

$W_\perp = mv_\perp^2/2$ to the magnetic induction B remains unchanged.

The ratio $W_\perp/B$ is called the adiabatic invariant. It is an invariant because it remains constant during the motion of a particle even if B changes. The word "adiabatic" means that the invariance is only satisfied if B varies smoothly enough. The necessary condition for the conservation of the adiabatic invariant is that the particle revolves many times before it arrives in the region with the very different magnetic induction B. The size of the magnetic trap is considerably larger than the radius of the Larmor circle, so this condition is safely satisfied and the adiabatic invariant is conserved with a high degree of accuracy. Thus a particle is confined within the trap and may keep on oscillating indefinitely between the two magnetic mirrors.

Unfortunately, this is true not for all particles. Let us imagine that the particle velocity is mainly directed along the magnetic induction so that when the particle is in the middle of the trap, nearly all its energy is concentrated in the longitudinal component and the energy $W_\perp$ of the transverse motion is quite small. As the particle approaches a mirror, the value of $W_\perp$ increases in direct proportion to the increase in the magnetic induction B. If, for example, the magnetic induction at the centre of the trap were B_0 and the maximum induc-

tion in the trap were B_{max}, the value of $W_\perp$ would increase to $W_{\perp\,max} = W_\perp B_{max}/B_0$. The energy of longitudinal motion thus decreases. But it might happen that at the instant the particle arrives at the point corresponding to the maximum induction, the energy of the particle's longitudinal motion and hence its longitudinal velocity may not be zero. This means that the particle will not come to a stop and will leave through the mirror. It can be shown that this fate will befall all particles whose velocities are at an angle smaller than α_{crit} to the direction of the magnetic induction, where $\sin\alpha_{crit} = \sqrt{B_0/B_{max}}$. If, for example, B_{max} is four times B_0, we get $\sin\alpha_{crit} = 1/2$ and hence $\alpha_{crit} = 30°$. In this case, all particles whose velocities lie within a 30° cone about the direction of the magnetic induction will leave the trap.

The existence of a loss cone is one of the main drawbacks of a magnetic mirror trap. Since the velocity of a particle may fall within the loss cone as a result of collisions, the confinement time for a particle within a trap with magnetic mirrors is found to be of the same order as the time between collisions.

The time between collisions of particles in a plasma decreases with increasing density and increases with temperature;

$$\tau = 3 \times 10^4\, T^{3/2}/n,$$

Hence the product $n\tau$ for a trap with magnetic mirrors is independent of density: $n\tau = \text{const} \times T^{3/2}$. Thus in order to increase the value of $n\tau$ for a trap, we must make the temperature as high as possible.

Since electrons are much lighter than ions, their velocities are higher and collisions more frequent than those of ions at the same temperature. Hence the electrons will come within the loss cone and leave the trap faster than ions. This leaves the trap with a net positive charge. The electric field of this charge prevents further electrons from leaving the trap and, on the other hand, increases the rate of escape of ions. Ultimately, a net charge is established with an equilibrium between the rate of loss of electrons and ions. This charge gives the plasma in a mirror trap a positive potential proportional in magnitude to the electron temperature T_e and depends logarithmically on the number density, temperature, and the mass of electrons and ions:

$$\Phi = 3.76 \times 10^{-5}\, T_e \log \left(\frac{n_e}{n_1} \sqrt{\frac{T_e M_1}{T_1 m_e}} \right).$$

From this we can obtain the following formula for calculating the product $n\tau$ in a magnetic mirror trap:

$$n\tau = 2.3 \times 10^{16} E_0^{3/2} \log \frac{B_{max}}{B_0}.$$

Here, E_0 is the energy in keV supplied by the external source to the ions entering the trap. It follows from this formula that the Lawson criterion is satisfied in a magnetic mirror trap if the ions have an energy of $E_0 \simeq 400$ keV.

First Experiments

Experiments with magnetic traps were first carried out in the early 1950s. In the first place, the ability of a magnetic mirror trap to confine individual charged particles had to be verified. These experiments were set up simultaneously and independently by S.N. Rodionov in the USSR and by G. Gibson, P. Jordan and E. Lauer in the USA.

In both experiments, the measurements showed that a magnetic mirror trap confines individual charged particles quite effectively: a particle traverses the distance between the mirrors several millions of times before leaving the trap, and it is only because of collisions with gas atoms left in the trap that particles last in the trap only for several seconds.

Encouraged by these results, scientists embarked upon experiments involving plasmas. At the first stage, the problem of filling the trap with a plasma had to be solved: after all, it is as difficult for a charged particle to enter an ideal trap as it is to

leave it! If the source is situated outside the trap, the particle will have a trajectory leading it out of the trap again. In order to prevent this from happening when the particles are confined within the trap, we must alter some of the parameters affecting the particle trajectories, such as the charge or mass of the particles or the magnetic induction in the trap.

The first method which involves a change in the particle mass was proposed by the Soviet scientist G.I. Budker in 1953 and was used in experiments on the Soviet Ogra and American DCX units.

The Ogra unit is the largest single trap constructed so far (Fig. 3.3). It has a vacuum chamber 1.4 m in diameter and 12 m long. The magnetic field in the centre of the trap may be as high as 0.5 T, while at the magnetic mirrors it may rise to 0.8 T. The size of the trap reflects the confidence of the scientists in the success of the experiment. It was believed that the setup would get close to a fusion reactor. The very term "Ogra" is an acronym from the Russian for "one gram of neutrons per day". This was the amount of neutrons the scientists expected to obtain during fusion reactions in the unit.

In the first experiments on the Ogra unit, a beam of molecular hydrogen ions H_2^+ was used to fill the trap with plasma. Budker's idea was that ions would be captured as a

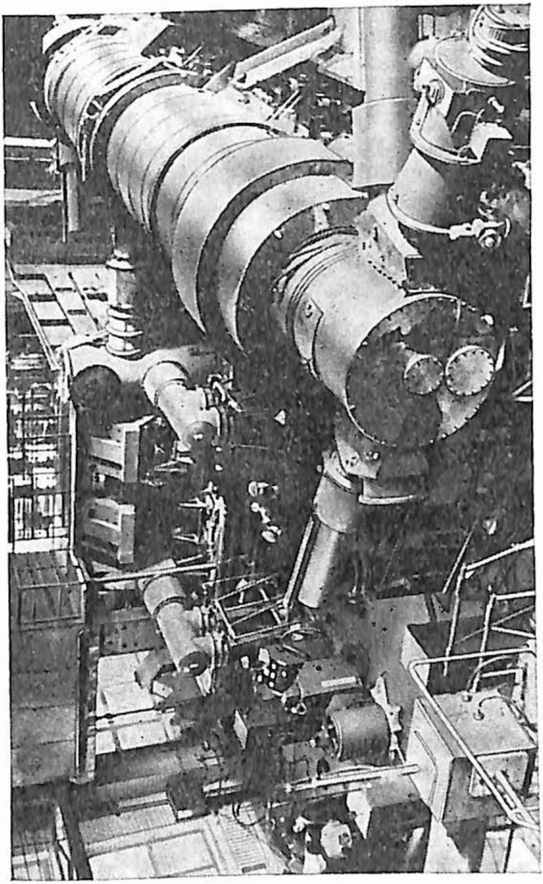


Fig. 3.3. Lay-out of the Ogra unit.

result of the dissociation of H_2^+ ions at atoms of the residual gas in the trap. This results in the formation of H^+ ions whose mass is half that of the H_2^+ ions. Hence the orbital radius of the H^+ ions in the magnetic field is halved and the ions are thus captured (Fig. 3.4).

In order to create a beam of H_2^+ ions, a source was placed near the trap and an

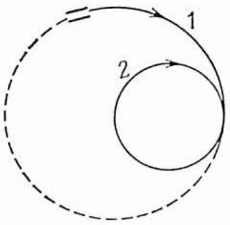


Fig. 3.4. Injection and capture of ions in a trap, based on the dissociation of molecular ions: *1*) molecular ion trajectory, *2*) atomic ion trajectory.

electric arc discharged. The H_2^+ ions were pulled out of the plasma generated by this discharge by an electric field and were accelerated to an energy of 160 keV. The ions flew into the magnetic field at an angle of 70° to the direction of the lines of force and moved inside the trap in a helical path. After dissociation, the radius of the helical trajectory sharply decreased and the ion could no longer reach the source during its motion in the trap. The trap was thus

gradually filled with a hot plasma of density 10^{13}-10^{14} m^{-3}.

Another ingenious method for filling the trap with a plasma was applied in another Soviet unit, viz. the PR-1 unit built under the supervision of M.S. Ioffe. This unit had much smaller dimensions than the

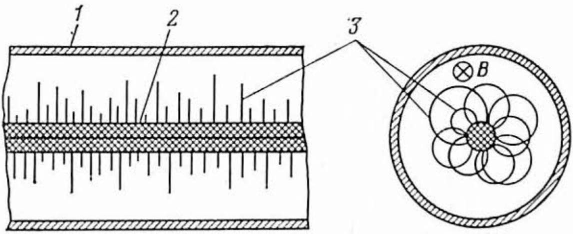


Fig. 3.5. Schematic diagram of the PR-1 device: *1*) chamber wall, *2*) cold plasma column, *3*) fast ions.

Ogra unit: the distance between the magnetic mirrors was about 1 m and the diameter of the vacuum chamber was 0.5 m. The magnetic field at the centre of the chamber was 0.2 T and near the mirrors it was 3.4 T. A cold plasma source was mounted at the centre of one of the mirrors (Fig. 3.5) to fill the trap with plasma. The plasma from the source propagated along the trap's axis. An electrode mounted in the second mirror was used to cause an electric arc along the cold plasma column. A voltage of up to 6000 V was then applied across both elec-

trodes and the walls of the vacuum chamber. This generated a radial electric field between the cold plasma column along the axis and the wall of the vacuum chamber. This field extracted the ions from the cold plasma and accelerated them. The magnetic field of the trap forced the ions into helical trajectories. The ions could not leave the trap through the mirrors since their velocities were nearly perpendicular to the magnetic field. Thus the ions were accumulated. The required number of electrons was produced by ionization of the residual gas filling the chamber. A plasma was thus produced in the trap.

After the feasibility of filling a trap with plasma had been proved, another trap, the PR-2 unit, was constructed with a higher magnetic induction and a better vacuum than in the PR-1 unit. The induction of the field in the new trap was 0.8 T at the centre and 1.25 T at the mirrors. New vacuum pumps made it possible to create a vacuum of 10^{-5} Pa. Good evacuation of the trap is very important for investigations of plasma confinement times because collisions between plasma particles and the residual gas increases the plasma density due to the ionization of its atoms, and, on the other hand, causes additional losses of hot ions due to charge exchange. Charge exchange is the transfer of an electron from one nucleus to another during a

collision between an atom and an ion. Hence a hot ion is transformed into a rapidly moving atom which can cross the magnetic field towards the wall. The former atom is transformed into a cold ion. All these processes distort the true picture of plasma confinement in a trap and hence a good vacuum is of prime importance. A plasma with a density 10^{14}-10^{15} m^{-3} was obtained in the PR-2 using the same technique that was employed in the PR-1. A temperature of 10^7 K was reached for the ions while the temperature of the electrons was 2×10^5 K. Given these plasma parameters the particles would last in the trap for several seconds if they can only leave the trap by falling into the loss cone due to collisions. Even if charge exchange with residual gas atoms is taken into account, the particles would last quite a long time.

In practice, the plasma particles lasted in the trap for a much shorter time than expected. Moreover, investigations showed that a large fraction of the plasma leaves the trap through the side walls across the magnetic field and not through the end mirrors.

This behaviour did not come as a surprise for the experimental physicists. Even before experiments on the PR-2 unit, the theoretical scientists, B.B. Kadomtsev in the USSR and M. Rosenbluth and I. Langmuir in the USA, predicted that the plasma

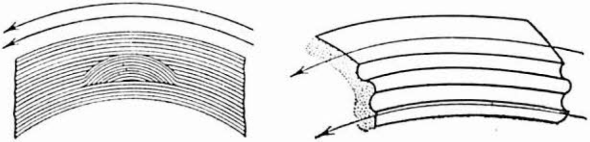
would be able to leave a magnetic mirror trap across the magnetic field and not only through the mirrors. The reason is again plasma instabilities, which were driving scientists mad during investigations on pinching discharges.

The instabilities of a plasma confined in a simple magnetic mirror trap are due to the diamagnetism of the plasma that allows it to be confined in the first place. Since a plasma is diamagnetic, the magnetic field acts on it with a force which expels the plasma from the region of high magnetic field to the region of weaker field. If we consider the motion of a plasma as a whole rather than the motion of individual particles, this force pushes the plasma from the mirrors towards the centre of the trap. And that is a good thing to happen to plasma!

However, the situation is different in the radial direction from the trap's axis. The magnetic induction is at a maximum on the trap's axis and decreases towards the side wall. The plasma may be in equilibrium under these conditions, but the equilibrium will be unstable. Suppose that a small protrusion in the form of a "tongue" protruding between the magnetic induction lines appears on the side surface of the plasma (Fig. 3.6). The plasma in the "tongue" gets into a region with a weaker magnetic field and starts protruding more and more under its own pressure into regions

where the magnetic field pressure is even lower, and so on. Ultimately, the "tongue" reaches the walls of the chamber and the plasma is extinguished.

This instability was termed "flute instability" because the protruding "tongue" between the magnetic induction lines is



(a) (b)

Fig. 3.6. Flute instability: (*a*) the "tongue" on the plasma surface and (*b*) the formation of grooves on the plasma surface.

accompanied by the formation of a groove or flute along the lines. The depth of the flute also tends to increase indefinitely. Since a certain amount of energy has to be spent to move the magnetic induction lines apart, a low-density plasma can still be confined, but the rate of plasma escape sharply increases with increasing plasma density.

There are regions in a magnetic mirror trap where the magnetic induction increases along the radius. Consequently, the plasma must be stable in these regions, which are located in the vicinity of the mirrors. In regions near the centre of the trap, the mag-

netic induction decreases along the radius. It is very easy to distinguish between these regions. Where the magnetic induction increases from the axis outwards, the magnetic induction lines are convex with respect to the plasma, whereas where it

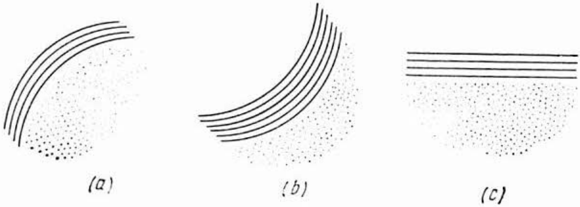


Fig. 3.7. Instability criterion for plasma confinement by a magnetic field: (*a*) unstable configuration, (*b*) stable configuration, and (*c*) neutral configuration.

decreases outwards, the induction lines are concave with respect to the plasma (Fig. 3.7). Hence it is possible to predict where the plasma will be stable and where it will be unstable.

All these detailed theoretical predictions were verified in experiments on the PR-2 and then on the Ogra. The behaviour of the plasma was found to be in agreement with the predictions of the theory. The instability developed where it was anticipated. The rate of growth of instability and the value of the critical plasma density, when the instability starts developing very

rapidly, were also found to be in good agreement with the theory. The results of these experiments were presented at the First International Conference on Plasma Physics and Controlled Nuclear Fusion Research at Salzburg in 1961. The discovery of flute instability had a considerable impact on the entire thermonuclear fusion problem. After all, this was the first time the complicated behaviour of plasma had been fully explained theoretically and a complete agreement between theory and experiment attained.

"Ioffe Bars". The "Minimum *B*" Principle

After the flute instability had been discovered and the mechanism of its emergence had been explained, attempts were made to eliminate it. Since the development of flute instability is linked with a decrease in the magnetic induction in the centre of the trap, the most radical way to fight the instability is to change the configuration of the magnetic field in such a way that the magnetic induction increases from the axis outwards. One of the first ideas was to reverse the current in one of the coils in an ordinary magnetic mirror trap, the device being called a trap with cusp configuration. The magnetic fields produced by the coils would then be directed against each other. The magnetic fields neutralize each other in

the centre of the trap and the magnetic induction is therefore equal to zero. The magnetic induction lines have a configuration shown in Fig. 3.8. It can be seen that the induction lines are always convex with respect to the plasma. Hence, the theory

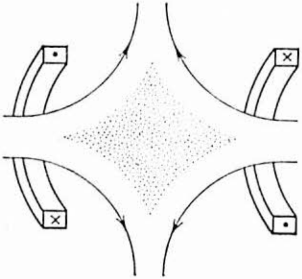


Fig. 3.8. Magnetic trap of cusp configuration.

predicts that no flute instability should appear in the plasma in a trap of this kind.

Experiments confirmed that this is indeed true. Nevertheless, plasma confinement times in traps with cusp configuration were still quite small. It turned out that the adiabatic invariant $W_{\perp}/B$ was not conserved at the centre of the trap where the magnetic induction vanishes. Hence the condition for the reflection of the particles in the magnetic mirrors is violated.

A different method was used by M.S. Ioffe and coworkers to change the configuration of the magnetic field. Additional conduc-

tors, called "Ioffe bars", were used. Six bars were arranged around the periphery of the trap parallel to its axis (Fig. 3.9). The currents flowing in the bars alternate in direction from one bar to the next. The

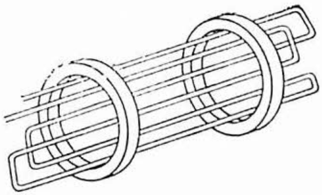


Fig. 3.9. Trap with "Ioffe bars".

magnetic field created by these conductors is superimposed on the magnetic field of the trap. As a result, the induction around the periphery of the trap can be increased by increasing the current in the conductors. At the same time, the total magnetic induction produced by all six conductors is always equal to zero at the trap's axis and hence the value of B_0 remains unchanged.

Experiments on plasma confinement on the new device (it was called the PR-5) showed that "Ioffe bars" work magnificently. In complete accord with the theory, as soon as the ratio of the induction B on the periphery to the induction B_0 on the axis was larger than unity, the loss rate decreased sharply and the plasma confinement

time in the trap increased significantly (Fig. 3.10).

These experiments had a considerable influence on fusion research. Not only was the plasma behaviour understood in detail, but it had been proved that the plasma

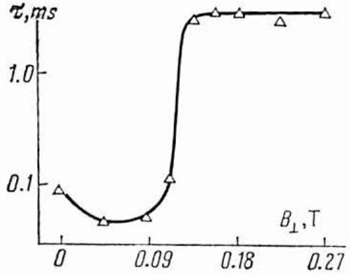


Fig. 3.10. Plasma confinement time in the PR-5 as the function of the transverse magnetic field.

could be externally controlled. The suppression of plasma instability by changing the magnetic field's configuration in such a way that the induction increases outwards from the plasma became a principal tool in other devices as well. When designing new magnetic traps, the validity of the "minimum B" principle is now always verified first. In other words, traps are always designed in such a way that the magnetic induction B has its minimum in the region occupied by the plasma and increases outwards

as far as possible in all directions from the plasma boundary. Of course, such a design is not always feasible.

In this case, attempts are made to ensure that the "minimum B" principle is satisfied at least on the average during motion along the lines of induction in the regions accessible to the plasma particles.

Several technical modifications were later introduced to the design of magnetic mirror traps with "Ioffe bars". At first, it was discovered that if the number of the bars is reduced from six to four, they and the coils producing the main field can be replaced by a single coil with a complex shape in which the current flows along the same path as in the original trap. The shape of the coil is analogous to the stitches on a tennis ball or baseball, whence the term] "baseball" (Fig. 3.11*d*).

Later, it was observed that the volume of plasma in a baseball trap can be considerably increased if we cut the coil into two halves and move the two halves slightly apart (Fig. 3.11*e*). A configuration resembling the Chinese hieroglyph Yin-Yang is obtained, and hence these coils were called Yin-Yang coils. The structure of the magnetic field in a trap with a baseball or Yin-Yang coil does not differ in principle from the field structure in a trap with "Ioffe bars". In this case also, the "minimum B" principle is obeyed. Hence this

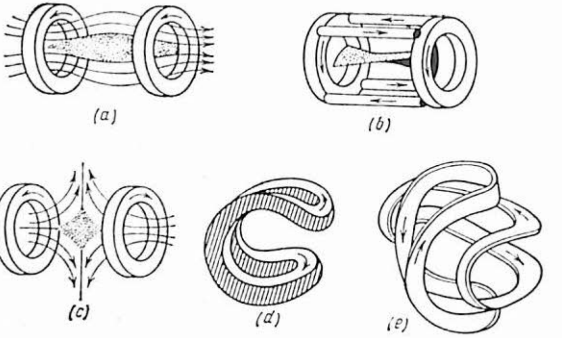


Fig. 3.11. Evolution of magnetic mirror traps: (*a*) simple magnetic mirror field, (*b*) Ioffe trap, (*c*) system with opposing fields, (*d*) baseball, and (*e*) Yin-Yang.

type of coil is often proposed in the design of fusion reactors.

In addition to varying the configuration of the magnetic field, the flute instability can also be eliminated by using electric fields to actively control the plasma's behaviour. This method was termed the "feedback method" by analogy with control theory. To exercise control over an animate or inanimate object, the feedback from the object being controlled is of prime importance. It enables the control system to find out the result of the controlling action, i.e. whether the situation has improved or deteriorated, and to take the necessary corrective measures. For example, when a per-

son wants to pick a pencil up from a table, he gets feedback from looking at his hand. With the help of this feedback, the brain controls the position of the hand relative to the target and corrects the movement of the muscles in such a way that the distance between the hand and the target is reduced.

A similar system was employed to suppress plasma instability in a trap. The motion of the plasma is controlled by an electric field which is generated by applying a voltage to electrodes surrounding the plasma in the trap. Signals from sensors measuring electric field oscillations in the plasma are used as the feedback. These signals are amplified and fed to the electrodes controlling the electric fields in the plasma. By varying the delay between the signal fed to the electrodes and the plasma signal, the plasma oscillations can be amplified or quenched.

The feedback method was first applied to eliminate the flute instability in the Soviet Ogra-II and Ogra-III devices, and also in the joint Anglo-Soviet operation of the English Phoenix-II unit. By suppressing flute instability in the Ogra-III, the plasma density was increased by a factor of 50. The feedback method was subsequently applied to other devices.

Other Instabilities

The plasma confinement time in magnetic mirror traps was increased by about 40-50 times as a result of the suppression of the flute instability, and the plasma losses were reduced to the same extent. However, other, more subtle, instabilities became noticeable. Unlike the flute instability, which is related to the motion of the plasma as a whole, these instabilities concern individual groups of particles. The motion of groups of particles is studied in the branch of mechanics called kinetics. Hence these instabilities are called kinetic instabilities.

Because they may fall into the loss cone, the particles have a nonequilibrium velocity distribution. There are much fewer particles with low velocities $v_\perp$ perpendicular to the magnetic field than there are particles with high velocities, while the situation is usually just the opposite in a gas or a plasma in the state of thermal equilibrium.

This instability is used in lasers, indeed laser radiation is generated because of the excess numbers of high-energy particles. Whereas considerable effort is required to obtain a nonequilibrium distribution of particles for laser generation, this sort of nonequilibrium state is attained automatically in a magnetic mirror trap.

Naturally, the excess numbers of high-energy particles lead to the generation of

waves as it does in lasing. The only difference between the two cases is that in lasers electromagnetic waves of radiofrequency or optical range are produced while in the magnetic mirror trap plasma waves are generated.

Kinetic instabilities were often observed when the plasma was created by injecting high-energy particles. The injected particles had an energy of several tens of thousand electronvolts in these experiments. The D + T reaction can occur very rapidly for particles with such high energies. The suppression of flute instabilities raised hopes that the accumulation of high-energy particles in a trap might yield a plasma with the reactor parameters.

However, it was found that particles are only accumulated in such units up to a certain density, viz. $\sim 10^{15}\ m^{-3}$. After this, the plasma begins to oscillate and the density does not increase any further in spite of a regular supply of particles from the injector. This behaviour was observed in the Soviet Ogra-II, the English Phoenix-II and the American Alice-Baseball.

Brute Force Method

By this time, beams of fast atoms began to be used to accumulate plasma. The atoms are ionized inside the trap and the resultant ions and electrons are captured by the

magnetic field. To start with, beams with moderate intensities were used, i.e. particle fluxes of about 10^{18} particles/s. If the particles were charged, the beam would carry an electric current of 0.15 A. The equivalent current in amperes is normally used to characterize the intensity of neutral atomic beams. A significant change occurred at the beginning of the 1970s in the technique for obtaining beams of fast neutral atoms. Sources capable of delivering tens of amperes of equivalent current were developed.

The new sources permitted scientists to tackle the problem of kinetic instabilities by the brute force method. Beams with intensities of tens of equivalent amperes generate higher plasma densities in the trap in spite of the instabilities. After a few milliseconds, the plasma density in the trap reaches up to 10^{20} m^{-3}. These results were obtained on the American 2 X IIB unit where the brute force method was used for the first time and a plasma was obtained with the ion density and temperature needed for a fusion reactor. In this case, the plasma pressure becomes comparable with the pressure of the magnetic field. Owing to the diamagnetism of the plasma, the magnetic induction at the centre of the trap decreases almost to zero. As a result, the ratio B_{max}/B increases and hence the confinement of particles becomes even better.

However, the situation was not so favourable for the energy confinement. The energy confinement time was found to be a few milliseconds and hence the product $n\tau$ was considerably lower than the Lawson criterion. The rapid cooling of the plasma ions in these experiments was due to the very low temperature of the electrons.

The temperature of the electrons in the 2 X IIB unit was low because of the injection of large amounts of cold plasma, or gas, which is converted into cold plasma in the trap. The cold plasma is required to overcome the kinetic instabilities, which would otherwise allow the rapid escape of hot particles from the trap. Hence further progress could be only made by improving the confinement of hot plasmas in magnetic mirror traps.

Tandem Traps

Suppose the difficult task of reducing the loss of particles through the magnetic mirrors could be undertaken by the plasma itself. This idea was put forth independently by the Soviet scientist G.I. Dimov in 1979 and, somewhat later, by the Americans R. Fowler and B. Logan.

We saw at the beginning of this chapter how electrons leave a trap more quickly than ions do because electron velocities are much higher at the same temperature than are ion velocities. Hence an excess positive

charge is created in the trap and the plasma acquires a potential $\Phi = 3.76 \times 10^{-5}\, T_e \times \log\left(\frac{n_e}{n_i}\sqrt{\frac{T_e M_i}{T_i m_e}}\right)$. The resultant electric field prevents the electrons from leaving the trap and accelerates the ions leaving it. In a simple magnetic mirror trap, this charge has very undesirable results in that the rate of ion loss increases and the confinement of electrons causes them to cool so that the departure of the electrons becomes nonuniform. This is because electrons with high energies overcome the ionic attraction and leave the trap while the coldest electrons remain in the trap.

In order to overcome the drawbacks, Dimov in 1976 proposed that three magnetic mirror traps should be used simultaneously instead of one trap with a common magnetic field. The plasma density in the outer traps is made much larger than that in the central trap as a result of a powerful injection of particles. The departure of particles through the outer traps' magnetic mirrors will produce an excess positive potential in the system of traps. This means that an excess negative charge will appear in the central trap due to a stronger flux of electrons from the outer traps to the central one than in the opposite direction. This negative charge produces an electric field, which improves the plasma confinement in the central trap.

This device was called a tandem trap since the outer and central traps effectively complement each other like the cyclists on a tandem.

The small outer traps create a volume charge that improves the ion confinement in the central trap. In turn, the flux of (relatively) cold plasma from the central trap fills the loss cone and removes the instability in the outer traps.

The plasma temperature in the central trap can be brought to the optimal value of 3×10^8 K from the point of view of the rate of fusion reactions. In this case, the necessary condition for the confinement of ions in this trap is that the negative charge must create a potential difference of about 100 kV between the central trap and the outer traps. To create this potential difference, the plasma density in the outer traps must be about thrice that in the central trap, and the ions being injected into the outer traps must have an energy of 1 or 2 MeV.

The energy spent to maintain the ion temperature in a tandem trap is mainly associated with the beam injection into the outer traps. In order to cover these losses, the central trap, in which the fusion reactions are to take place, must be made quite large, with the central trap having to be over 100 m long. However, the design of the unit can be very simple—the magne-

tic field in the central trap may be uniform and not very strong, since the plasma density in the central trap is not very high. A complex magnetic field pattern to ensure the "minimum B" condition for the entire system is only required in the small volume of the outer traps (Fig. 3.12).

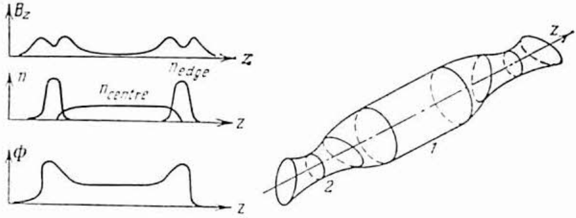


Fig. 3.12. Tandem trap. Distributions of magnetic induction, plasma density, electric potential, and magnetic field configuration: *1*) central solenoid with a weak field, *2*) trap with the "minimum B" field at the ends.

Thus a fusion reactor based on a tandem trap promised to be simple in design and cheap.

These remarkable prospects inspired scientists to investigate the physical processes in tandem traps with a view to verify the basic ideas underlying them. About a couple of years after the idea was put forth, construction of tandem traps was started in the USSR, the USA, and Japan. The first moderate-size traps were ready at the beginning of the 1980s and investigations were started.

The experiments confirmed the main idea of a tandem trap, viz. that the difference in densities between the plasmas in the outer and central traps produces an electric field which significantly improves the plasma confinement in the central trap.

The particle and the energy confinement time near the trap's axis were found to be in good agreement with the theoretical calculations made by the Soviet scientist V.P. Pastukhov. However, the loss rate at the plasma's periphery was found to be quite high, thus indicating the development of an instability in the region. The task now facing scientists is to study the mechanism of the increased losses and to eliminate them. The plasma parameters attained in the first units ($n \simeq 3 \times 10^{19}$ m^{-3}, $T \simeq 1.5 \times 10^6$ K) and the energy confinement time ($\tau_E \simeq 5 \times 10^{-4}$ s) are fairly modest at present.

Far more impressive results should be attained in the next generation of devices, which are being constructed at present. One such device is under construction at the Siberian Division of the USSR Academy of Sciences in Novosibirsk, and has been given the name Ambal. The plasma temperature in the Ambal is expected to be about 10^7 K.

Extensive investigations are being carried out in the USSR on magnetic mirror traps. Experiments on plasma confinement in

"classical traps" are being carried out on the Ogra-IV unit.

The Ogra-IV unit has a superconducting baseball magnetic system. The plasma is created using four injectors of neutral atoms with energies of 15-30 keV and an equivalent current up to 20 A. The plasma oscillations and the mechanism of the losses through the magnetic mirrors under the "minimum B" condition are being investigated. Methods for overcoming these drawbacks are being worked out.

An idea for overcoming cone instability by rotating the plasma is being tried in Novosibirsk on the PSP-2 device. A strong radial electric field is created and so the plasma is made to rotate rapidly about the longitudinal axis of the trap. The ratio of the transverse velocity of the particles to the longitudinal velocity increases and the losses through the loss cone are reduced.

Another device constructed in Novosibirsk, viz. the GOL-3, is intended to test the "wall confinement" idea. This device is a long chain of simple magnetic mirror traps, the length of the chain exceeding the mean free path of ions and electrons constituting the plasma. A particle entering the loss cone would therefore collide before it could leave the trap. As a result of the collision, the direction the particle is moving in changes and it remains in the plasma. According to calculations, to get the

fusion parameters of the plasma the trap must be 100-200 m long. The idea of transverse confinement underlying the construction of this unit is even more interesting. The plasma density is increased to such an extent that its pressure exceeds the pressure of the magnetic field, i.e. $\beta > 1$. We know that, under this condition, the magnetic field can no longer confine the plasma. The scientists at Novosibirsk, however, are undeterred by this prospect. They believe that the plasma will be confined by the steel tube of the device. The magnetic field in the unit serves only to decrease the loss by heat conduction.

If this idea proves to be fruitful, fusion reactors using a multi-mirror trap with wall confinement will be by far the simplest in design and economy.

Looking at the Battlefield Map!

Studies of magnetic mirror traps have already been going on for 25 years and enormous progress has been made. A millionfold increase in the plasma density has been obtained since the first traps were introduced, and the plasma temperature has been raised to the required level for fusion reactors. The quantity $n\tau$ is the only parameter which has yet to be brought up to the required value (Fig. 3.13). But even in this direction significant progress has

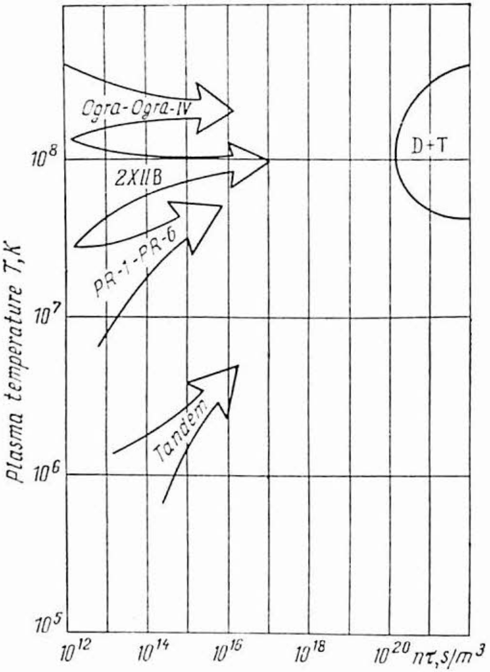


Fig. 3.13. Battlefield map showing that the goal is still far away.

been made. A detailed study of the physics of plasma confinement has revealed the mechanisms of the losses and ways of overcoming them. Thus investigations using the magnetic mirror traps have contributed significantly towards a better understanding

of plasma physics and facilitated progress in other fields.

The notable improvements in plasma confinement technique have made magnetic mirror traps a possible basis for fusion reactors. Their main advantages are their simplicity of design and their economy since the plasma can be confined at $\beta \simeq 1$.

Of course, quite a lot of work has still to be done before these advantages can be realized in a practical way. The value of $n\tau$ has to be increased by a factor of about 1000 by improving the plasma confinement time. The large number of pioneering ideas and the scale of the investigations being carried out in many laboratories all over the world leave no doubt that these difficulties will be surmounted and the construction of a fusion reactor based on magnetic mirror confinement before the end of this century remains a clear possibility.

Chapter 4

Stellarator

Let's Close the Trap!

The most radical method for eliminating the plasma losses through the ends of a magnetic mirror trap is to get rid of the ends entirely. This can be done by curling the trap into a ring and joining the ends. The trap then becomes doughnut-shaped, or as the mathematicians would say, a torus (Fig. 4.1).

However, a simple torus with a magnetic field will not work as a magnetic trap. The problem is that the magnetic field becomes inhomogeneous when a straight tube is bent into a ring. It is stronger inside the ring and weaker on the outside. As we saw in Chap. 1, a drift arises when charged particles move in an inhomogeneous field, that is the particles gradually move perpendicularly to the direction of the field's inhomogeneity. Positively charged particles collect at the bottom of the tube and negatively charged ones at the top. As a result an electric field is generated directed vertically upwards. The charged particles must therefore move in two fields, a magnetic one directed along the tube and a verti-

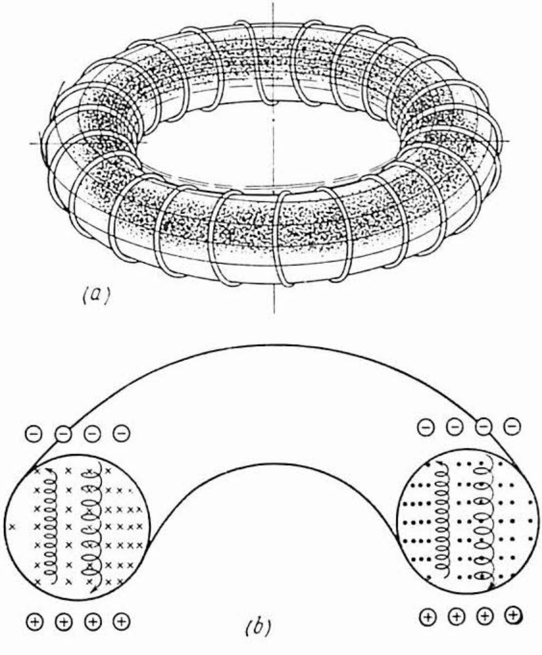


Fig. 4.1. (*a*) Magnetic trap in the form of a torus and (*b*) its cross-section. Charges get separated in the toroidal trap due to magnetic field nonuniformity.

cal electric one. The trajectories of the particles then become helices which spread horizontally towards the outer walls of the torus with each turn. Consequently, the plasma quickly hits the walls.

This complicated analysis of the motion of charged particles in a toroidal magnetic field was carried out in 1950 by Soviet and American scientists. It was suggested by the Soviet scientists that an electric current should be passed through the plasma to prevent the toroidal drift.

The magnetic trap constructed on the basis of this suggestion was subsequently called a tokamak. Today, tokamaks offer the most promising method for magnetic confining a plasma. We shall describe tokamaks in detail in Chap. 5.

The development of magnetic confinement techniques in the USA was started by L. Spitzer, a noted astrophysicist who had carried out a detailed investigation of the movement of plasmas in interstellar magnetic fields. Having discovered the shortcomings of toroidal magnetic fields, Spitzer presented a method for overcoming them. He proposed that the torus should be twisted into a figure-of-eight. The trap would then act like two tori connected in such a way that a charged particle in the trap moves clockwise round one torus and anticlockwise round the other torus. As a result, the particle drift is neutralized.

The magnetic lines of force in the trap are not closed after one turn of the trap. This means that charged plasma particles can move from the upper part of the tube to the lower part and vice versa as they

move along the magnetic field lines. This prevents a separation of the particles and the emergence of a vertical electric field that has such unfortunate results in a simple toroidal trap (Fig. 4.2). The trap should be able to hold charged particles very well.

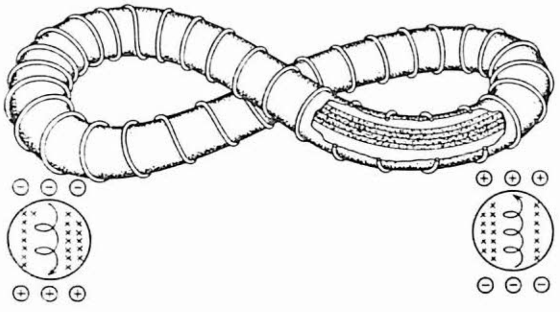


Fig. 4.2. Bending the torus into a figure-of-eight results in a mutual compensation of excess charges generated by the drift of particles.

Spitzer assigned a beautiful name for his trap: he called it a stellarator (stellar torus) to indicate that the fusion reactions taking place in the trap must be the same as those taking place in stars. In 1951, Spitzer put forward proposals for a comprehensive programme to obtain controlled fusion using stellarators. These proposals were adopted and investigations were started soon afterwards.

The programme was in four stages and envisaged the successive construction of stellarators of ever increasing dimensions. Each stage was designed to solve a definite range of problems.

The stellarator A was a small model with a weak magnetic field intended to verify whether charged particles like electrons could be confined in such a trap.

The next model, the stellarator B, had a vacuum chamber 5 cm in diameter. It produced a magnetic field of 3 T and could deal with plasma.

The next stage, the stellarator C, had a vacuum chamber 20 cm in diameter and a magnetic field of 5 T. It was intended to be a quarter of the actual size of a fusion reactor.

Finally, the stellarator D was supposed to be a prototype fusion reactor in which thermonuclear energy was to be produced in quite large amounts.

The stellarator programme research was carried through quite actively and the stellarator A was constructed by 1952. The experiments confirmed the validity of the basic idea, viz. the ability of a stellarator to confine charged particles. What is more, experiments with plasma were even carried out on this device. The plasma was produced by the electric breakdown of a gas. In keeping with the theoretical predictions, it

was found that a gas in a figure-of-eight trap is broken down more easily than it is in a simple torus.

The stellarator B-1 was constructed in 1954 and the high magnetic field immediately posed a number of specific problems. The strong force due to the magnetic pressure distorted the magnetic coil and the vacuum chamber and strong fastenings had to be devised to withstand these forces. After this, experiments involving plasma were carried out. The problem of impurities cropped up at this stage. For reasons that were not clear at that time, the plasma interacted very strongly with the walls of the vacuum chamber. Although the vacuum chamber was initially filled with pure hydrogen, considerable amounts of carbon, silicon, and oxygen were found in the plasma after the discharge was switched on. The ions of these impurities glowed very brightly. All the energy liberated during the passage of an electric current through the plasma and which was intended to heat the plasma to the required temperature was carried away by the impurity glow to the vacuum chamber walls.

The unit had to be redesigned to eliminate this problem. The porcelain vacuum chamber was replaced by a stainless steel tube. Very powerful high-vacuum pumps were used to evacuate the chamber. This reduced somewhat the energy losses due to

impurity emission and it became possible at least to obtain a discharge.

Contactless methods for studying plasma were first investigated on this unit. Until then a wire probe was introduced into the plasma to measure its density and temperature. The wire probe method had been developed by the American scientist I. Langmuir in the 1920s in studying gas discharges. The plasma temperatures in these discharges did not exceed a few thousand degrees Kelvin and Langmuir probes made of refractory metals (tungsten or molybdenum) served the scientists faithfully for several decades. However, temperatures of the order of millions of degrees Kelvin were involved in fusion reactors, and even the most refractory probes become useless in plasmas at such temperature.

However, since a plasma reflects radiowaves like metals, its density can be measured by irradiating it with a beam of radiowaves. A low-density plasma is transparent to radiowaves, but it has a certain critical density for each wavelength at which waves with that wavelength are reflected by the plasma and the beam of radiowaves no longer passes through it. For radiowaves having a wavelength of 1 cm, the plasma has a critical density of about 10^{19} m^{-3}, while a plasma with a density of 10^{20} m^{-3}, the value required in a fusion reactor, reflects waves with a wavelength

of 3 mm. Using a set of generators with different wavelengths, the instants when the signal from each generator ceases show when the plasma density reaches these critical values (Fig. 4.3).

This method of measuring a plasma density allows the generator and the receiver

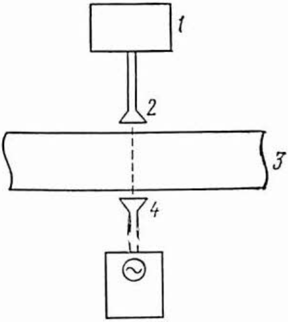


Fig. 4.3. Measurement of plasma density by passing radiowaves through the plasma: *1*) generator, *2*) emitter, *3*) plasma, *4*) receiver.

to be located quite a distance from the plasma and hence there is no direct contact between the plasma and any solid material. Hence this method of measurement of plasma density is applicable at all temperatures.

Spectroscopy is another contactless method and it had been developed long before the advent of plasmas. By studying a plasma's radiation spectrum, its composition

can be determined. Although the main component (hydrogen nuclei) does not emit radiation, all the impurities can be clearly seen. The concentration of the impurity ions can be determined from the intensity of their emission lines, and the moments they appear in the plasma can be determined.

It was found that impurity lines emerge at quite definite times during the discharge. The times were when the discharge current exceeds a critical value which had been determined earlier by the English physicist M.D. Kruskal and the Soviet physicist V.D. Shafranov for pinching discharges. Each time the discharge current exceeds the Shafranov-Kruskal critical value, the plasma developed a severe instability. The plasma breaks through the magnetic field and touches the walls of the vacuum chamber and the impurity atoms vaporizing from the walls flash brightly.

The B-series stellarators devised in the wake of B-1 (the B-2, B-64, B-65, B-3), were all mainly directed at the elimination of the instabilities and impurities appearing in the plasma from the walls. During this period, many important aspects concerning the operation of closed systems were clarified, and special devices and methods were worked out to eliminate the impurities. Many of these devices are still used today not only in stellarators, but also in tokamaks, indeed, they will probably be insep-

arable parts of any fusion reactor based on a closed magnetic trap. We shall consider some of these in greater detail later.

Divertor

A device called a divertor was used for the first time in the B-series stellarators to eliminate the impurities appearing in the plasma from the walls of the vacuum chamber.

A diagram of a divertor is shown in Fig. 4.4. Using an auxiliary coil, some of the magnetic field lines are driven from the vacuum chamber of the stellarator into a special divertor chamber. Here a thick water-cooled receiver plate is placed at right angles to the magnetic field lines.

Plasma particles encountering these field lines (the so-called divertor layer) move freely along them and enter the divertor chamber, where the plasma is quenched when it comes in contact with the receiver plate. Most of the impurities the plasma liberates from the receiver plate remain in the divertor chamber which is evacuated by a powerful vacuum pump. Only some of the impurities, which fly accidently in the right direction, return through the entrance window to the main part of the stellarator containing the plasma.

Tests of the device showed that the idea was basically correct and the flux of impurities appearing in the plasma was reduced significantly by the inclusion of a divertor.

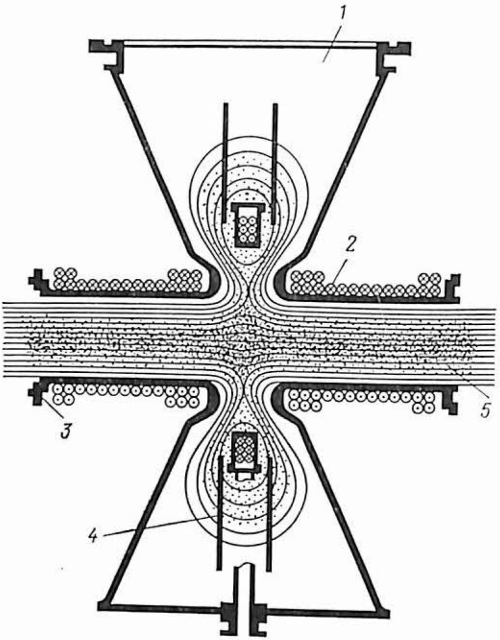


Fig. 4.4. Divertor. Some of the magnetic field lines near the plasma surface are deflected into a separate chamber by an additional winding. Properly cooled plates are placed in the path of the plasma in this chamber. The plasma coming into contact with the plates is cooled and converted into a neutral gas which is pumped out: *1*) outlet to the diffusion pump, *2*) magnetic field coil, *3*) the stellarator's tube walls, *4*) collector plates, *5*) discharge chamber.

Helical Winding. Shear

The American theoretical physicist E. Teller discovered in 1954 that the figure-of-eight magnetic field in a stellarator is unstable with respect to perturbations in the plasma along a helical line. It turned out the plasma acquires a "tongue" which winds itself helically with exactly the same lead as that of the magnetic field lines.

The "tongue" easily separates the lines of force and pass through them without coming into contact with any of the lines. The plasma can thus reach the wall and events then follow a familiar course: a small quantity of the material of the wall is vaporized and impurities appear in the plasma, which is rapidly cooled as a result of the emission of the radiation.

Teller's theory greatly affected the leaders of the stellarator project. Further research on the design of the stellarator C was discontinued and a research group at Princeton was entrusted with the task of finding a deterrent against the Teller instability.

Once again, it was Spitzer who came up with an idea for the deterrent. He concluded that the magnetic field lines in the stellarator must be inclined at different angles in each layer. In this case, a plasma "tongue" aligned in the direction of the magnetic field lines in one layer will run into field

lines in the next layer because they are at a different angle. Hence the "tongue" cannot reach the wall without intersecting the field line (Fig. 4.5). Spitzer proposed that the design of the stellarator be completely altered to implement this idea.

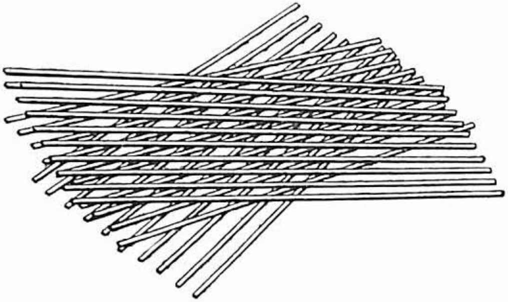


Fig. 4.5. Variation of the rotation angle of the magnetic field lines with "shear" radius.

The vacuum chamber took on the shape of a plane figure resembling a racetrack in a stadium, i.e. two semicircles connected by straight tracks (racetrack configuration).

A helical winding formed by several pairs of conductors is wound around the semicircular segments of the tube. The current flows in one direction through half of the conductors and in the opposite direction through the other half.

The helical winding makes the magnetic field lines turn around the chamber's axis,

the inner layers of the field lines turning more slowly than the outer layers. This results in a cross-linking of the field lines. This phenomenon was termed "shear". Let us follow the motion of a charged particle located in a stellarator, say, at point *1* (Fig. 4.6*a*). As it moves along the field line,

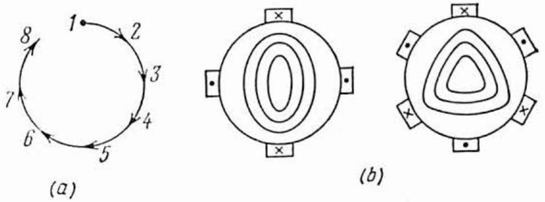


Fig. 4.6. (*a*) Rotation of magnetic field lines in a stellarator and (*b*) magnetic surfaces of stellarators with two and three pairs of helical conductors.

the particle will travel around the stellarator and return to the cross-section where we began to follow.

The field lines are rotated by the current flowing through a helical winding and hence instead of returning to point *1* the field line returns to point *2*, having thus turned through a certain angle i. After the next turn, the line returns to point *3*, and so on. If we take the intersections of the field line with the cross-section over a very large number of times, we find that these points lie on a closed curve. All the points on the curve are obtained by following a

single field line for a large number of turns around the stellarator. The field line forms a closed surface whose cross-section is nothing else but the field line itself.

The shape of the magnetic surfaces depends on the number of pairs of conductors in the helical winding. If the winding has two pairs of conductors, the magnetic surface will be elliptical. If there are three pairs, the magnetic surface will be triangular with rounded edges, and so on (Fig. 4.6*b*). The vertices of the triangle or the narrow ends of the ellipse lie under the conductors in which the direction of the current coincides with that of the magnetic field (if the helical winding is clockwise).

If we move along the magnetic field, the ellipse or the triangle rotates together with the helical winding. The intrinsic magnetic surface passes through each point inside the stellarator chamber and hence a multilayer magnetic insulation is formed by the magnetic surfaces, each lying within the other.

Experiments on the B-65 device and the small Étude stellarator with a helical winding showed that a helical winding does cause the rotation of field lines and shear.

After this, experiments were carried out involving a plasma. The investigations showed that the plasma stability is improved by the introduction of shear. However,

the particles continue leave the plasma rapidly and the impurity flux from the walls remains quite significant.

One reason behind the small lifetime of the plasma is simply because the diameter of the vacuum chambers in the B-series stellarators was small (just about 5 cm).

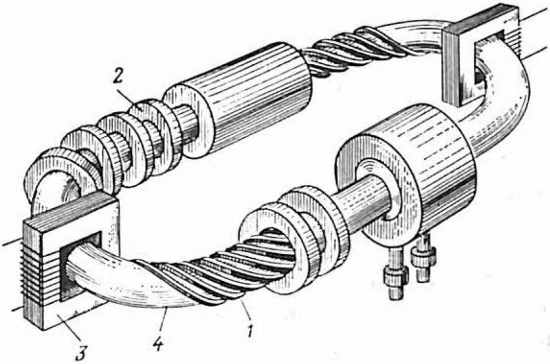


Fig. 4.7. Stellarator C: *1*) helical winding, *2*) longitudinal field coils, *3*) ohmic heat transformer, *4*) vacuum chamber.

The short time required by the particles to cover the 1-2 cm separating them from the walls does not allow them to be heated to any significant temperature.

These arguments led to the renewal of the research programme on the construction of a larger stellarator (the stellarator C). The stellarator C had imposing dimensions and the vacuum chamber, of the racetrack

configuration as in the B-65 stellarator, was 13.5 m long. The plasma had a diameter of 20 cm and the magnetic induction could be increased to 3 T. The stellarator was equipped with a divertor and an antenna to heat the plasma ions by radiowaves (Fig. 4.7).

The Beginning of Cooperation

The initiative of the Soviet Union caused the veil of secrecy surrounding fusion research to be lifted at about this time. In 1958, the Second International Conference on the Peaceful Uses of Atomic Energy was held under the auspices of the United Nations. The results of investigations on the B-series stellarators were presented at the conference and the stellarator programme evoked considerable interest among the participants. Although a large number of problems remained unsolved, the feasibility of the idea was beyond any doubt and progress towards an understanding of the plasma behaviour in stellarators could clearly be seen.

The next conference, viz. the First International Conference on Plasma Physics and Controlled Nuclear Fusion Research, was held at Salzburg, Austria, in 1961. This conference was devoted solely to fusion research. The reports once again covered experiments on the American B-se-

ries stellarators as well as initial results obtained on the C stellarator.

However, stellarator research had already started in other countries as well.

In Munich (FRG), investigations of plasma confinement began with a repetition of the experiments carried out by the American scientists. The first German stellarator has the same shape as the American C stellarator, viz. a racetrack configuration, but it was quite small in size. The radius of curvature was just 35 cm and the vacuum chamber had a diameter of 4 cm. The helical field was produced by a helical winding consisting of three pairs of conductors. Like all its successors, the German stellarator was termed Wendelstein-1 after the highest peak in the Alps in the FRG.

The first experiments on the Wendelstein-1 were not very successful—the plasma departed from the trap remarkably rapidly.

Two German theorists, D. Pfirsch and A. Schlüter, were able to find the reason for the increased rate of plasma loss due to the bend in the tube with the stellarator field. Their theory was only applicable to very cold plasmas, but the experiments were carried out using a cold cesium plasma.

It follows from Pfirsch-Schlüter theory that a helical winding with three pairs of conductors does not rotate the magnetic

field lines sufficiently. It was decided to replace the winding by a helical winding consisting of two pairs of conductors. The new unit was called Wendelstein-1B, and the first one was renamed the Wendelstein-1A.

The experiments on the new device were more successful. Plasma losses from the trap were so small that even the additional perishing of plasma on a 0.1-mm wire introduced into the plasma to measure its density became noticeable against their background. These results were reported at the International Conference on Plasma Physics and Controlled Nuclear Fusion Research in 1965.

In the Soviet Union, a stellarator programme was started in 1962. The first stellarator L-1 was built at the Lebedev Physical Institute of the USSR Academy of Sciences.

Unlike American and German stellarators of the time, the Soviet stellarator was perfectly round without any straight sections, viz. racetracks. Having analyzed the experience of the German and American scientists, the Soviet researchers decided from the very outset to do without the racetracks because of the magnetic field distortions which could considerably deteriorate the plasma confinement and which are inevitable in the transition region from the rounded sections to the racetracks.

This theoretical conclusion had been drawn before the stellarator was constructed. Three years later (in 1965), German researchers came to the same conclusion after their experiments on the Wendelstein-1B stellarator.

At the same time, a stellarator programme was also started at the Kharkov Physico-Technical Institute. In 1964, the Sirius stellarator was put in operation. It has a racetrack configuration and a winding with three pairs of helical conductors. An analysis of the magnetic field structure in this stellarator showed that closed magnetic surfaces were indeed formed within it.

In 1965, the Second International Conference on Plasma Physics and Controlled Nuclear Fusion Research was held in the UK and a large number of reports on stellarators were presented. American scientists presented their latest results on the stellarator C. The plasma confinement in the device remained poor. Moreover, an analysis of the confinement time as a function of plasma temperature and magnetic induction yielded the rather pessimistic formula $\tau = 4a^2B/T$, where a is the plasma radius, B is the magnetic field's induction, and T is the plasma temperature. This formula was proposed by the American physicist D. Bohm. The decrease in the plasma confinement time with increasing temperature, predicted by the Bohm for-

mula, cast a doubt over the possibility of controlled fusion. The temperature had to be increased at least by a factor of 100, while the plasma confinement times in the stellarator C were 1000 times shorter than those required.

The results obtained on the Soviet L-1 and Sirius stellarators looked much better. The plasma confinement time in the L-1 stellarator was several times longer than the time calculated by using the Bohm formula. The plasma confinement time in the Sirius stellarator was close to the time calculated by the Bohm formula for a high plasma density, but as the plasma density was reduced, the confinement time increased. The promising results obtained on Soviet stellarators inspired English physicists to start investigations on this design. To begin with, they decided to verify whether a stellarator is indeed an ideal trap for individual charged particles. For this purpose, a small toroidal stellarator, called the Clasp, with a winding having three pairs of helical conductors, was designed. Charged particles were introduced into the trap with the help of the method which had been used to verify the confinement of particles in a magnetic mirror trap. The trap was filled with the gas tritium, viz. a radioactive hydrogen isotope. Neutral tritium atoms freely passed through the magnetic field to the trap, while ^3He nuclei and electrons

formed during the decay of tritium were trapped by the magnetic field. Charged particles were confined in the trap for more than 10 000 000 cycles. If a plasma could be confined in a stellarator for as long as individual charged particles could be, this would be sufficient for the operation of a fusion reactor.

The success of this experiment encouraged the English scientists to design a larger stellarator on the same scale as the stellarator C, but purely toroidal in shape and without racetracks. The new stellarator was named the Cleo, but since they had no experience of operation with large-scale stellarators, they did not venture to start with such a large device and decided to construct a smaller device first. The little device was called the Protocleo. It was a small stellarator with a winding having three pairs of helical conductors. The torus radius and the plasma radius were 40 cm and 5 cm, respectively.

The Third International Conference on Plasma Physics and Controlled Nuclear Fusion Research was held in 1968 in Novosibirsk. By that time, the stellarator programme had become worldwide. The experimental results reported at this conference could be divided into two groups, namely, the Soviet, German and English experiments, on the one hand, and the American experiments, on the other hand.

The first group covered work done on quite small devices and attempts were made to explain the physics of plasma confinement and heating in stellarators. Despite the rather modest plasma parameters attained at this stage ($n \simeq 10^{18}$ m^{-3} and $T \simeq 200\,000$ K), the reports were optimistic.

A clear dependence of the plasma confinement time on the structure of the magnetic field was demonstrated on the Soviet L-1 stellarator. In these experiments, the plasma confinement time as a function of the magnetic induction of the helical field was investigated. A change in the current in the helical winding caused the variation in the rotation angle of magnetic field lines. The plasma confinement time increased with the rotation angle, as should be expected from theory.

However, the report on the experiments conducted on the biggest stellarator, viz. on the American stellarator C, was rather pessimistic. The plasma confinement time for the stellarator C continued to follow the Bohm formula and energy losses were so large that even additional and very powerful high-frequency heating could not elevate the plasma temperature to above 1.5×10^6 K. According to the Bohm formula, increasing the temperature still further would further increase the energy losses.

The theoretical reports were no less pessimistic for the stellarator programme. The

Soviet theoretical physicists A.A. Galeev, R.Z. Sagdeev, and L.M. Kovrizhnykh established that stellarators, like other toroidal traps, cannot confine all plasma particles equally well. Since the magnetic field in the trap is nonuniform (it is stronger in some regions and weaker in others), small

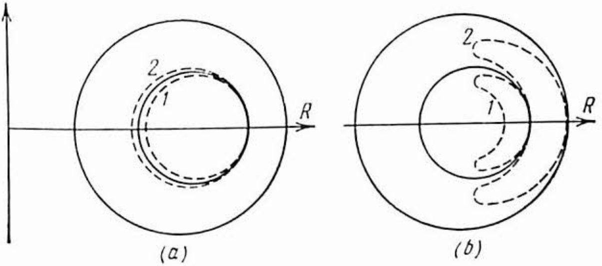


Fig. 4.8. Projection of drift trajectories of charged (*a*) passing and (*b*) trapped particles. A particle describes either trajectory *1* or *2* depending on the direction of its longitudinal velocity relative to the direction of the magnetic field.

magnetic mirror-type traps are spontaneously formed within the torus and may catch some of the plasma particles. A particle confined between two magnetic mirrors oscillates back and forth and cannot, unlike other particles, travel around the torus. For this reason, the trajectories of the trapped particles differ from those of remaining particles (unfortunately, this is unfavourable).

If we look along the torus, the trajectory of a trapped particle would remind a banana (Fig. 4.8). The "banana" deviates a considerable distance away from the magnetic surface along which a passing particle would move if it would have not been trapped. Well, so what? The particle moves in a closed path and cannot leave it. This is true, but only for as long as the particle moves freely. If it collides with another particle, the trapped particle starts to describe a new trajectory from the point of collision, being immediately displaced by the thickness of the banana in the process. Since a banana can stretch over a significant portion of the plasma radius, the trapped particles can leave the plasma within only a few collisions.

This mechanism of particle escape increases the loss rate in a stellarator by an order of magnitude. The heat transfer rate increases to the same extent because a trapped particle moving in a banana trajectory transfers heat from the hot centre of the plasma to the cold periphery.

Trapped particles did not have a significant role to play in the devices at that time, but when the calculations were made for a fusion plasma, the predictions of the theory were frightening. The thing is that the number of trapped particles depends on the collision frequency.

A particle becomes trapped only when the ratio of the velocity component $v_{\parallel}$

along the magnetic field to the velocity component $v_\perp$ across field is small:

$$\frac{v_\parallel}{v_\perp} < \sqrt{\frac{B_{max} - B_{min}}{B_{min}}},$$

and the ratio of the number of such particles to the total number of particles is

$$\frac{N_{trap}}{N_{tot}} = \sqrt{\frac{B_{max} - B_{min}}{B_{max}}}.$$

This is the same as the condition for a magnetic trap (see Chap. 3). The only difference is that we were happy with such particles since they were the ones confined in the magnetic mirror trap. However, in a stellarator such particles become trapped and leave the plasma soon.

Fortunately, the variation in the magnetic field in a stellarator is not strong. The maximum field B_{max} and the minimum field B_{min} differ from the average field only by a few percent, so that the ratio $(B_{max} - B_{min})/B_{min}$ is normally about 0.1. Hence a particle becomes trapped if $v_\parallel/v_\perp < \sqrt{0.1} \simeq 0.3$ for it. The number of trapped particles is also about 0.3 of the total number.

After each collision, the ratio $v_\parallel/v_\perp$ changes. Therefore, after a collision a trapped particle may stop being trapped and will safely fly around the torus, without describing its banana trajectory.

At high collision frequencies, the particles remain trapped for such a short time that nothing is left of the bananas, and there is no increase in the energy loss due to trapped particles.

The collision frequency drops with increasing temperature. Therefore, as the temperature is raised from 10^5 K (at which the plasma experiments were carried out at that time) to 10^8 K needed in a fusion reactor, the collision frequency must drop by a factor of 10^4. For this reason, the prediction of the banana catastrophe for stellarators was menacing.

While Neighbours Flourish

At the Novosibirsk Conference, the results obtained by Soviet scientists on tokamaks (devices allied to stellarators) caused a sensation.

The structure of the magnetic field in a tokamak is very close to that in a stellarator. The only difference is that the magnetic field lines are rotated by the current flowing directly through the plasma and not by an external helical winding. The closed magnetic surfaces formed in this case are the same as those in a stellarator.

The design of a tokamak is much simpler than that of a stellarator. The essential features of a tokamak are a simple toroidal magnetic field, a plasma, and a current.

The term "tokamak" is the acronym of the Russian expression for current, chamber, and magnetic coils. It had always been assumed that the plasma confinement in a tokamak would be inferior to that in a stellarator since, should anything happen to the plasma, the current would also change, and hence the structure of the magnetic field confining the plasma would be violated. The perfidity of the plasma is such that we can easily predict how it will react to its confinement: it will wriggle its way free to the walls.

This was the case during the first investigations on tokamaks. However, Academician L.A. Artsimovich, who headed the research, remarked that, on the other hand, the design of the tokamak is much simpler and so it is easier to explain the behaviour of the plasma in the tokamak than in the stellarator. Thus, the tokamak experiments were continued in spite of the setbacks. This, however, will be described in the next chapter.

What is important for us now is that the patience and perseverance of "tokamakers" in their battle against the crafty plasma were rewarded. They reported at the Novosibirsk Conference in 1968 that they had finally managed to overcome the "radiation barrier" below which almost all the supplied energy was spent on the impurity radiation. As soon as they learned how to

obtain a discharge with fewer impurities, the plasma temperature started to grow. According to the Soviet measurements, the plasma temperature in the T-3 tokamak had been raised to 10 million degrees Kelvin, almost ten times higher than the best results obtained on stellarators (Fig. 4.9).

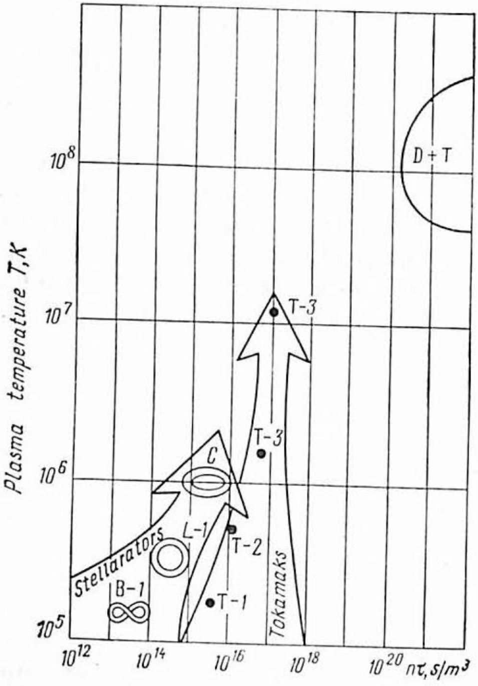


Fig. 4.9. This is how the situation looked like by the year of 1969.

This was a severe jolt for the stellarator programme.

The American scientists did not want to believe the results and the methods used to measure the plasma temperature and the other plasma parameters were hotly disputed at the conference. The Americans were eager to find an error in the measurements made by their Soviet colleagues, but alas, not a single error could be found. After the conference, several English scientists were invited to work on the T-3 tokamak. They were asked to measure the most important plasma parameter, viz. the plasma temperature, independently of the Soviet researchers. In 1969, the results of the joint work of the Soviet and English scientists were published. The English laser measurements confirmed the measurements made by the Soviet scientists by other methods. The plasma temperature in the tokamak was sometimes even higher than 10 million degrees Kelvin! This result had made a very deep impression on the American fusion researchers. The necessary measures were taken at once and with true American determination, and all work on the stellarator programme in the USA was discontinued. It was decided to reconstruct the largest stellarator C into a tokamak.

Chapter 5

Tokamak

The idea of tokamak was borne out of a whirlpool of ideas. To be more precise, the idea evolved in dialectic manner, in a spiral course. Even in the first theoretical papers on controlled nuclear fusion in the USSR, where the principle of the magnetic confinement of plasma was formulated for the first time, a fusion reactor surprisingly similar to a tokamak was designed, although scientists came around to the tokamak design only 30 years later.

In 1951, when these calculations were made, the reactor was assumed to be a torus with a major radius $R = 12$ m and a plasma radius $a = 2$ m. The plasma was to be confined by a magnetic field with an induction of up to 5 T. In order to eliminate the particle drift in the toroidal field and to heat the plasma, an electric current was to be passed along the torus directly through the plasma.

As is known, the magnetic field of this current causes the field lines to rotate and indeed this solves the problem of particle drift in a toroidal field. Thus, had such

a reactor been constructed at the time it could have operated! At any rate, the plasma confinement time in the reactor would be quite long. True, the required relation between the current and magnetic field was unknown at that time. Besides, the project was oriented around the D + D reaction rather than the D + T reaction. In general, so little was known at that time about plasmas that, naturally, nobody endeavoured to construct such a huge and expensive device straightaway, and the project was merely regarded as an illustration of the basic idea of magnetic confinement.

The idea of passing current directly through the plasma naturally had led to the idea of a pinching discharge (see Chap. 2), which at first glance seemed to be much simpler and hence more attractive. The main research efforts at controlled nuclear fusion were initially concentrated in this direction.

After scientists had become disillusioned with pinching discharges due to their instability, it was decided to return to an external magnetic field to eliminate the instability of the plasma column.

In 1952, V.D. Shafranov formulated the condition under which a discharge can be stabilized by a magnetic field. After the secrecy was lifted from the fusion problem, it was found out that a similar con-

dition had been derived independently by the English physicist M. Kruskal. Hence, the stability condition is known as the Shafranov-Kruskal criterion (it was mentioned earlier).

The magnitude of the stabilizing longitudinal magnetic field B_0 should be chosen depending on the plasma parameters and on the magnetic field B_I produced by the current flowing in the plasma:

$$B_0 > B_1 \frac{R}{a}.$$

In other words, the ratio $B_0 a/B_1 R = q$ must be larger than unity. The quantity q is called the safety factor and is important in the physics of plasma confinement in tokamaks.

Experiments on the stabilization of direct discharges by longitudinal magnetic fields were carried out under the guidance of I.N. Golovin and N.A. Yavlinskii, and they showed that there is stabilization. The main problem was to raise the plasma temperature. This, however, was hampered by the huge heat losses due primarily to heat transfer along the discharge to the end electrodes. In order to eliminate these losses, it was natural to look at a toroidal discharge.

But here scientists came face to face with another nuisance.

Balloon Effect

The tubes in automobile tyres have the same shape as the toroidal chamber of a tokamak, and all drivers know that when they inflate a tyre, the air pressure stretches the rubber on the outer surface much more than it stretches the rubber on the inner surface. As a result, the major diameter of the tube increases.

The reason behind this effect is very simple: the area of the outer surface is larger, and hence the force produced on it by the air pressure is stronger.

In the case of the tyre, this force is compensated by the elasticity of the rubber, but in the case of plasma, something must be added to compensate for the balloon effect, otherwise the toroidal plasma column will expand until it breaks down.

Two solutions were quickly found to the balloon problem. G.I. Budker proposed that another external magnetic field B_z be applied to a plasma loop along the axis of the torus (Fig. 5.1). The interaction of this field with the current flowing in the plasma results in a force directed into the centre of the plasma column. With an appropriate choice of the transverse field, the force may just compensate for the balloon effect.

The other suggestion was to enclose the plasma loop in a conducting copper casing.

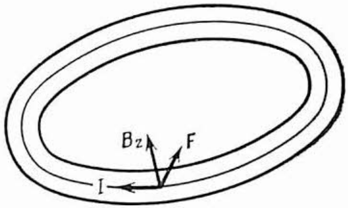


Fig. 5.1. A force neutralizing the balloon effect acts on the plasma current in a transverse magnetic field.

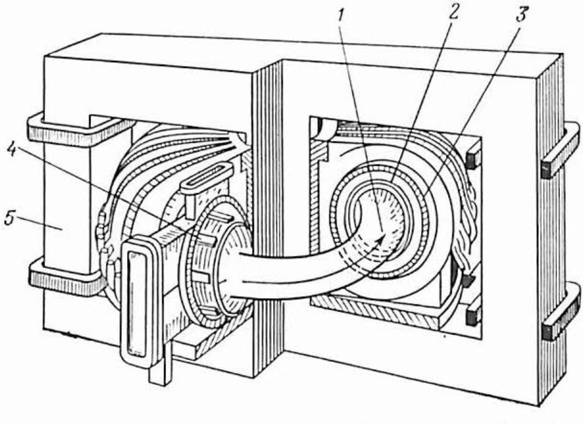


Fig. 5.2. Schematic diagram of a tokamak: *1*) plasma, *2*) stainless steel chamber, *3*) copper casing, *4*) transverse field winding, *5*) transformer for exciting plasma current.

Then any displacement of the plasma loop in the copper casing would give rise to eddy currents which would produce forces strong enough to return the plasma loop back (Fig. 5.2). Unfortunately, copper's resistance is nonzero, the eddy currents in the copper casing are gradually attenuated, and so the stabilizing effect of the copper casing vanishes with time. The duration of the stabilization depends on the thickness of the copper casing. While designing the first devices, a copper casing was chosen because the discharge duration in the casing amounted to a few milliseconds, hence a copper casing a few centimetres thick would ensure a sufficiently long stabilizing effect.

Childhood

The first tokamak was constructed in 1956 and the device was called the TMP (abbreviation for the Russian "toroid in a magnetic field"), the word "tokamak" not then being in use. A discharge was obtained with great difficulty, the main obstacle being an enormous impurity radiation which drained almost all the input power from the plasma. Under these conditions, the plasma temperature could not be raised by any means to above a few hundred thousand degrees Kelvin. In order to move further, the radiation barrier had to be overcome.

Naturally, a spectrograph was first used to find out what was emitting so brightly in the plasma. It turned out to be silicon. The vacuum chamber of the first tokamak was made of porcelain and so silicon was entering the discharge due to the evaporization of the porcelain. The problem of the vacuum chamber was solved in these experiments. This solution was so good that it is still in use in modern tokamaks. The vacuum chamber was made of stainless steel (Fig. 5.2). Stainless steel has a rather high resistance. Therefore, if very thin sheets of stainless steel are used to manufacture the chamber (the wall thickness can be of the order of a few tenths of a millimetre), the chamber can be made in one piece, without a seam.

Thus we obtain a closed loop, but because it has a high resistance, the current flowing through it is much weaker than the plasma current, and it will not overwork the transformer.

Tokamak-1

A device with a stainless steel chamber was called the Tokamak-1. But by an irony of fate, the first experiments on this device nearly drew entire programme away from tokamaks.

What happened was that in 1958, just when the Tokamak-1 was put in operation,

the results of studies on the English Zeta device were published. The Zeta was a large device with a closed pinching discharge in a weak magnetic field. Owing to the stabilization of the discharge by the magnetic field, the English scientists were able to obtain good results. At any rate, the results were more impressive than those obtained on the TMP. Since the geometry of the Tokamak-1 was generally the same as that of the Zeta (a closed vacuum chamber with a high-power transformer in the middle), the scientists were tempted to reproduce the results obtained on the Zeta. An attempt to do this was indeed made and it was quite simple, requiring only a reduction in the magnetic field by an order of magnitude. The results were about the same as those obtained on the Zeta. However, the Tokamak-1 could generate a much stronger magnetic field. This was also done and the experiment proved that a discharge in a strong magnetic field is more stable than in a weak field.

These experiments provided another important result: the first agreement with the predictions of a theory. The use of the strong magnetic field meant that the safety factor q was larger. It turned out that as soon as $q > 1$, the discharge stability indeed improved sharply in conformity with the Shafranov-Kruskal criterion.

However, it was too early to rejoice.

The plasma temperature in the stainless steel chamber still remained too low. Besides, the input power, as before, was drained from the plasma by the impurity radiation. The only difference was that the impurities were different. A spectroscopic analysis showed that the plasma now contained plenty of oxygen and carbon. It was a mystery. The reference books say that stainless steel consists of iron, nickel, chromium, etc., but there is no word about oxygen or carbon.

The situation was explained by vacuum engineers. There is a layer of other molecules such as those of oxygen, nitrogen, carbon dioxide, and water on the surface of any metal. The phenomenon has been known for a long time and is called adsorption.

Adsorbed molecules adhere to the surface of a solid due to the forces of molecular attraction. When the surface of a solid is in contact with air, various molecules constituting air collide with the surface and stuck to it.

The adhesive forces acting on the molecules on the surface of a solid are quite strong. The adsorbed molecules can be removed by heating the body to a few hundred degrees Celsius and this degassing technique is employed, for example, when manufacturing vacuum valves.

A similar problem faced those working

on the stellarator programme. The vacuum chamber of the stellarator B-1 was heated in vacuum to 450°C. As a result, the flow of oxygen and carbon atoms into the plasma was reduced by about a factor of 100.

In order to reduce the impurity inflow to the plasma of the B-1 still further, a

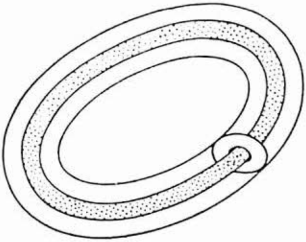


Fig. 5.3. A diaphragm restricts the diameter of the plasma column.

diaphragm (a plate mounted across the chamber) was used. The aperture in the diaphragm restricts the discharge diameter so that the plasma does not touch the walls of the vacuum chamber and only interacts with the diaphragm. The area of the surface in contact with the plasma sharply decreases, and hence the impurity inflow is reduced (Fig. 5.3).

The experience gained on the stellarator programme could be applied to tokamaks due to the international cooperation and information exchange on fusion research. In 1959, the T-2 device was made with

a stainless steel chamber that could be heated to 450°C and containing a diaphragm.

These measures considerably reduced the number of impurities and their radiated power. However, a new calamity struck—the plasma density started to drop during the discharge.

Spectral measurements showed that the tokamak plasma was indeed mainly hydrogen (the concentrations of oxygen and carbon impurities being only 5-10%). Hydrogen ions, on leaving the plasma, stick to the walls of the vacuum chamber, and the plasma density drops. Earlier, when the plasma was considerably contaminated, every hydrogen ion colliding with the surface knocked out a hydrogen, oxygen or carbon atom. As a result, the plasma density increased instead of decreasing, and by the end of the discharge the plasma density was much higher than the density of the hydrogen filling the chamber before the discharge.

With a clean chamber, everything was turned upside down, i.e. the density of the plasma by the end of a discharge was lower than the initial density of the hydrogen. Moreover, after the end of the discharge, when all the plasma ions had been neutralized and converted into atoms, the hydrogen pressure was 1/10th of the pressure before the discharge!

Well, the calamity was not very serious. A valve was installed in the chamber through which hydrogen was added during the discharge so that the plasma density grew instead of decreasing. The tokamak was given a few correcting coils to stabilize and control the position of the plasma in the chamber.

In spring 1962, K.A. Razumova and E.P. Gorbunov working on a new TM-2 tokamak device, managed to obtain a plasma column that remained stable up to the end of the discharge during entire two milliseconds! The stable discharges were only obtained at the maximum value of the magnetic field of 2.2 T and for a sufficiently weak current. The safety factor (you remember the quantity q?) should have been about 8 instead of 1 according to the Shafranov-Kruskal criterion, and yet stable discharges were obtained! This was a brilliant success.

An attempt to increase the discharge current, and hence to reduce the value of q from 8 to 4-6 resulted in what the authors called the disruptive instability. Like the sword of Damocles, this instability continues to hang above the heads of tokamak researchers.

During a disruptive instability the plasma abruptly flares up and the discharge voltage drops. These flashes are very short in duration (about a tenth

of a millisecond) and between the flashes the plasma is quite calm. Spectroscopic analysis shows that at the moment of disruption the interaction between the plasma and the diaphragm and the chamber walls becomes much stronger, and hydrogen and impurity atoms enter the plasma from the walls.

The mechanism of disruptive instability was not easy to explain and even now, more than 20 years later, it still remains unclear to a certain extent. Although at the time the reasons behind the disruptions were not understood, attempts were made at least to avoid them.

Several more tokamaks were designed in order to broaden the field of activity. The most outstanding was the T-3 tokamak which worked until 1978 after several modifications (T-3A and T-4) (Fig. 5.4).

As one scientist has remarked operating with a tokamak is like cruising on a sailboat in stormy seas. Many hazards assault the experimentalist from all sides. The tokamak's plasma responds vigorously to the slightest variation in the experimental conditions, and it is extremely difficult to find stability islands in the stormy seas of the instabilities.

At the same time, the theory of plasma instabilities in tokamaks was advancing. The number of theoretically predicted instabilities could soon be counted in the

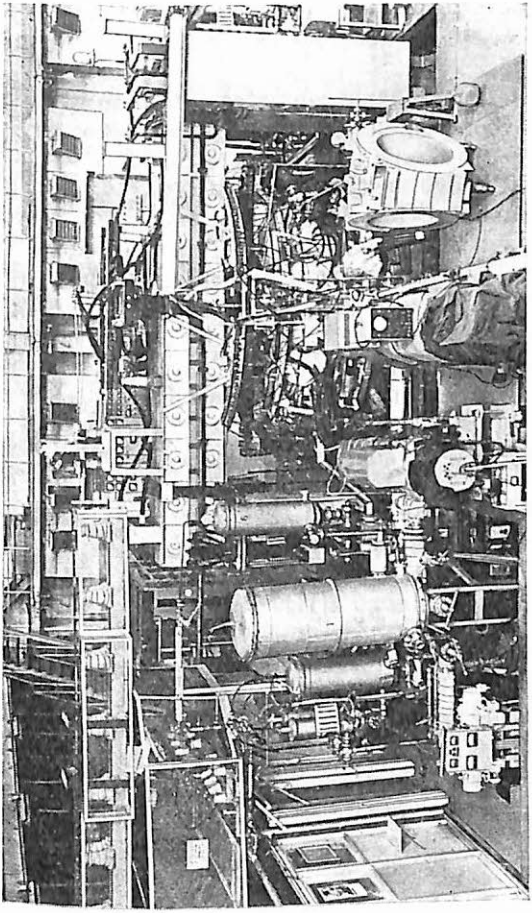


Fig. 5.4. General view of the T-4 tokamak.

dozens and it became necessary to classify them. Instabilities were divided into classes and types, as is done in zoology.

The most dangerous class of instabilities are those when the plasma starts to move as a whole and splashes onto the walls; it is known as the magnetohydrodynamic instability. The term reflects the fact that the plasma behaves in this case like a fluid, and its motion can be described by the equations of hydrodynamics (naturally, taking into account the effect of the magnetic field).

Magnetohydrodynamic (or MHD) instabilities are old acquaintances and worried physicists during experiments with pinching discharges (see Chap. 2).

For example, if the current passing through a plasma is too strong and the Shafranov-Kruskal condition is violated ($q > 1$), a helical MHD instability emerges. The plasma column becomes screw shaped, and if the vacuum chamber containing the discharge is not big enough, the plasma column may touch the wall with all the consequences we know.

A further evolution of the MHD instability theory as applied to tokamaks showed that the helical instability not only emerges when $q = 1$; in general it arises every time q is equal to an integer m or to the ratio of two integers m/n, for which the

screw would have m starts and n periods over the torus circumference (Fig. 5.5).

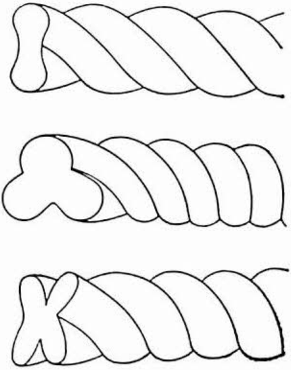


Fig. 5.5. The plasma assumes the form of a two-, three- or four-threaded helix.

This screw has a cross-section in the form of a flower with petals (Fig. 5.6). In

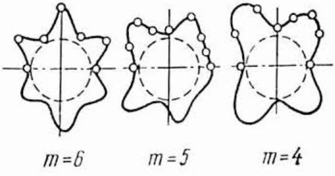


Fig. 5.6. Perturbations in the magnetic field due to the evolution of helical modes at the initial stage of the discharge.

a straight cylindrical discharge, these petals would be arranged uniformly in a circle, but when the cylinder is curved into

a torus, the petals diverge at the outer circle and converge at the inner circle, and the flower becomes asymmetric.

This beautiful theory emerged later to explain results from experiments. Plasma transformations into screws and flowers were first observed experimentally. The helical shape of the plasma surface was first observed in the TM-2 tokamak by N.D. Vinogradova and K.A. Razumova. They photographed the discharge with a high-speed camera and observed helical perturbations with $m = 3$. The petals moved over the plasma surface, passing the window through which the plasma was being photographed. Sometimes, immediately before a disruption, another screw with $m = 2$ could be discerned in the bulk of the plasma.

The helical instabilities in tokamak plasmas were analyzed in more detail on the T-3 tokamak by S.V. Mirnov and I.B. Semenov. They used magnetic probes in the form of tiny coils containing a few wire turns, which allowed them to measure the magnetic field of the plasma current. These probes are now known as Mirnov coils. Several dozen such coils were arranged on the outer surface of the torus and by comparing the signals induced by the plasma current in the different coils, information was obtained about the current in the vicinity of each coil, and hence the current distribution over the plasma current cross-

section was reconstructed. The points in Fig. 5.6 are the measurements using the Mirnov coils.

The measurements revealed that the cross-section of the plasma column indeed acquires the shape of a flower with different numbers of petals. The value of q is inversely proportional to the plasma current: $q = 5 \times 10^6 B_0 a^2/IR$. Therefore, at the beginning of the discharge, when $I = 0$, q is formally equal to infinity. As the current increases, q gradually decreases, taking on at times integer values. Each time this happens a helical mode arises so that the cross-section of the plasma becomes flower-shaped with respectively six, five and four petals.

It was revealed experimentally and then confirmed theoretically that a stable discharge can only be obtained if the plasma current is such that no flower is formed, i.e. q is not equal to an integer.

As a result of this work, this mysterious behaviour of the plasma became clearer. Concluding a review of the theoretical papers at the Second International Conference on Plasma Physics and Controlled Nuclear Fusion Research in the UK in 1965, Academician B.B. Kadomtsev remarked that the instability problem, which once seemed to be an uncrossable ocean, is after all no more than a vast lake whose outlines had been descerned. However, the experimental plasma parameters remained

too low. Although the strongest types of instability had been overcome, the plasma's behaviour could not be completely controlled in experiments. Energy losses in the plasma remained significant given the slightest inaccuracy in the selection of the controlling magnetic fields, insufficient cleaning of the vacuum chamber, or for some other unclear reason. In spite of the huge input power (up to 10^5 W), the plasma could only be heated to a few million degrees Kelvin and the energy lifetime in the plasma was about a millisecond. This value was several times greater than what was predicted by the notorious Bohm formula.

Tokamaks prevail three years later at the Third International Conference on Plasma Physics and Controlled Nuclear Fusion Research in Novosibirsk.

All the laborious work in the quest of instability islands, the selection of the value of the magnetic field, and the cleaning and degassing of the vacuum chamber walls was crowned by a phenomenal success: a plasma with a density of 5×10^{19} m^{-3}, which is only half the value required for a fusion reactor, was obtained in the T-3 tokamak. The electron temperature had reached eight million degrees Kelvin. while the ion temperature was five million degrees Kelvin.

The plasma with such parameters was

obtained in a discharge with a current of 120 kA and a magnetic field of 3.7 T. The lifetime of the hot plasma had reached ten milliseconds. These data indicated that the heat losses in the T-3 were 1/30th of those predicted by the Bohm formula. Besides, the dependence of the thermal conductivity of the plasma on the temperature and magnetic field also differs from that predicted by the Bohm formula.

This indicated that a calm plasma had been obtained in the T-3 tokamak, and the Bohm formula, which describes the behaviour of a turbulent plasma, is not relevant to the tokamak plasma. This result strongly contradicts those obtained on the largest American device, the stellarator C, where, as before, no thing the experimentalists could do could significantly improve their results over those predicted by the Bohm formula.

Results obtained on the German Wendelstein-2A stellarator were also reported at this conference. German scientists obtained a cold barium plasma with a temperature of about two thousand degrees Kelvin which lasted 10 times longer than it should have done according to the Bohm formula.

This enabled Academician L.A. Artsimovich, who headed the Soviet delegation, to bring the conference to a close on an optimistic note. He believed that the main

result of experimentalists working on closed traps was that they had "torn away from the gloomy fantom of enormous losses contained in the Bohm formula and paved the way for a further increase in the plasma temperature, leading to the attainment of the physical nuclear fusion level".

Chapter 6

The Heating Problem

A Tokamak in Every Household

Following the triumph of the T-3 tokamak, a craze for tokamaks engulfed plasma laboratories all over the world. Every country involved in nuclear fusion research started to build tokamaks.

The first tokamak beyond the border of the Soviet Union was built in the Princeton (USA) and called the ST. Many parts from the stellarator C were used to construct it, and this was why it was put into operation so quickly. Experiments on the ST were started in 1970, and a year later the results were reported at the International Conference on Plasma Physics and Controlled Nuclear Fusion Research in Madison (USA).

The ST was similar in size and structure to the Soviet T-3 device and the Americans were aiming to reproduce the results obtained on the T-3. They succeeded and for the first time in the history of nuclear fusion research results obtained on two different devices coincided.

This indicated that physicists had finally learned how to measure plasma parameters and how to control (sometimes) the behaviour of the plasma.

In their experiments on the ST tokamak, the American physicists themselves obtained results which disproved the Bohm formula, in which they had formerly so

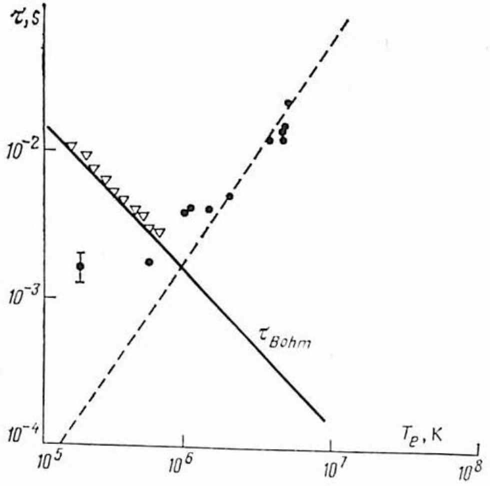


Fig. 6.1. Comparison of the temperature dependences of the plasma confinement time in the stellarator C (▽) and the ST tokamak (·).

firmly believed. The temperature dependence of the lifetime of plasma particles turned out to be inverse to that predicted by the Bohm formula. As the plasma temperature was elevated, the particle confinement time in the ST increased rapidly, while the Bohm formula predicted that it should decrease (Fig. 6.1).

The experiments carried out on various Soviet tokamaks, viz. the TM-3, T-3A, and T-4, allowed Academician L.A. Artsimovich to derive his famous formula for calculating the ion temperature in a tokamak plasma from the size of the tokamak, the value of the magnetic field, the plasma density, and the current.

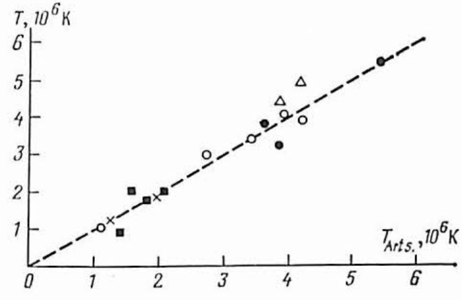


Fig. 6.2. Comparison of ion temperature in different tokamaks with the temperature predicted by Artsimovich's formula.

Figure 6.2 shows the ion temperature calculated using Artsimovich's formula and the values measured in experiments on the TM-3, T-3A, and T-4 tokamaks.

The good agreement between theory and experiment, and the consistency of the results between the T-3 and ST experiments indicated that the behaviour of the plasma had been clarified to a certain extent.

Using the relationships established in these experiments, researchers tried to estimate the parameters at which a plasma with a fusion temperature and density could be obtained in a tokamak.

It turned out that in spite of the favourable relationship between the confinement time and the plasma temperature and density, it would be hardly possible to attain the fusion temperature of 100 million degrees Kelvin using only current heating in a tokamak.

As a matter of fact, the electric resistance of a plasma rapidly drops with increasing temperature. In accordance with Joule's law, the amount of heat liberated in the plasma due to a current passing through it is proportional to the resistance: $Q = I^2Rt$. Therefore, as the plasma temperature increases, the same current causes the evolution of the smaller and smaller amounts of heat. The heat losses in the plasma grow. Even if we assume that the plasma is perfectly pure, it will still emit X-rays as a result of collision of electrons with ions. The energy losses associated with this radiation equals the heat evolution in the plasma already at a plasma temperature of 20 million degrees Kelvin, and the temperature stops growing.

It is impossible to increase the current to elevate the plasma temperature because the Shafranov-Kruskal stability criterion

will be violated. If the plasma loses its stability, it will cool completely instead of being heated due to contact between the plasma and the walls. True, the current can be increased without violating the Shafranov-Kruskal criterion by simultaneously increasing the magnetic field. Indeed, the Shafranov-Kruskal criterion contains the ratio of the plasma current to the magnetic induction: I/B. By increasing B, we can increase I in the same proportion without altering their ratio. Calculations show that in this way it is possible to elevate the plasma temperature to the desired 100 million degrees Kelvin, but then the value of the magnetic induction must be as high as 16 T.

Even stronger magnetic fields have been obtained in laboratories. However, a fusion device would require this magnetic field throughout a considerable volume, and this is not simple, but enthusiasts were found.

The enthusiasm displayed by Professor B. Coppi of the Massachusetts Institute of Technology brought into being a tokamak with a strong magnetic field called the Alcator. The device was even slightly smaller than the Soviet T-3 tokamak, but the magnetic induction of the field could reach 9 T, which was three times the corresponding value for the T-3.

Accordingly, the plasma current could be increased without bothering about the

plasma instability. The high heating rate made it possible to obtain a plasma with a record high density of 10^{21} m^{-3} on the Alcator. Since the plasma confinement time increases with the plasma density, a record value of the product $n\tau_E = 3 \times 10^{19}$ s/m^3 was attained on this device. This is only a few times smaller than the desired value $n\tau_E \simeq 2 \times 10^{20}$ s/m^3, which is required, according to Lawson's criterion, for a fusion reactor. True, the plasma temperature in these experiments was not high, viz. about 10^7 K. Therefore, an auxiliary method of heating is required in addition to plasma current to attain controlled fusion conditions in this device.

How to Heat Plasmas

New methods to heat the plasma confined in closed magnetic traps have been looked for throughout the history of nuclear fusion research.

As far back as 1950, L. Spitzer, the inventor of stellarator, proposed a "magnetic pumping" method for heating plasmas. The method involved an additional winding which was intended to generate an alternating magnetic field and mounted over a section of the tube. The pressure of the additional field compresses the plasma and pushes it along the tube into the unaffected region (Fig. 6.3).

Since the trap is closed, the accelerated plasma travels around the device to return to the region affected by the winding. If the frequency in the winding is chosen so that at this moment the current in the winding is at a maximum, the new impetus ac-

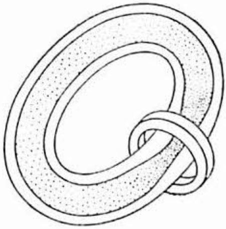


Fig. 6.3. Plasma heating by magnetic pumping.

celerates the plasma still further, and so on. Due to this resonance, the energy of the magnetic field is transformed into the energy of the moving plasma.

As a result of collision between the plasma particles, the directional motion is gradually converted into chaotic motion, i.e. the kinetic energy of the moving plasma will be converted into thermal energy.

This method was tested at the beginning of the 1960s on the stellarator C, but it proved to be too weak to make up for the heat lost as a result of the poor plasma confinement on the stellarator. Later, magnetic pumping was used to heat a plasma on the Petula tokamak in Grenoble (France).

The experiment was successful and the plasma temperature was raised by 50 000 degrees Kelvin per kilowatt of "pumping" power absorbed by the plasma. In this experiment, the ion temperature was raised by 600 000 degrees Kelvin, viz. from 2 to 2.6 million degrees Kelvin. Magnetic pumping has a number of advantages over other methods, which will be discussed later (the high efficiency of heating, and a convenient frequency range from 150 to 200 kHz for which high-power generators are available). However, the method has a considerable drawback since a complex antenna containing a large number of turns has to be introduced into the plasma column in order to supply power to it. For this reason, this method is inapplicable for the operation of a future fusion reactor.

Adiabatic Compression

Another method which was also worked out quite early is the adiabatic compression of the plasma. The term "adiabatic" means that it must be very rapid so that the energy of the compression has no time to escape from the plasma. This method is similar in principle to magnetic pumping, but in magnetic pumping the varying component of the magnetic field constitutes only a small fraction of the main field, which remains constant. For this reason, the plasma is

only slightly compressed and expanded during the magnetic pumping, but it occurs at a high frequency.

During adiabatic compression, the plasma is compressed just once, but this compression is very strong. The main magnetic field confining the plasma is made to vary.

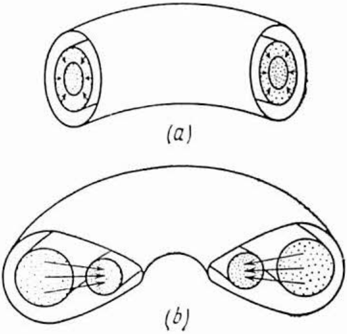


Fig. 6.4. Adiabatic compression of a plasma.

It is increased very rapidly so that it is multiplied several fold within a few milliseconds.

Plasma can be compressed in various ways. If the toroidal magnetic field is increased rapidly, the plasma will contract along the minor radius, and a thin ring-shaped plasma column will be formed (Fig. 6.4*a*).

The plasma can also be compressed along the major radius by rapidly increasing

the transverse (vertical) magnetic field rather than the longitudinal field. The plasma then contracts into a ring of a minor radius (Fig. 6.4*b*).

The experiments on the adiabatic plasma compression along the minor radius were carried out on the Soviet Tuman-2 tokamak in Leningrad and on the English Tosca tokamak. Plasma heating using the adiabatic compression along the major radius was studied on the American ATC tokamak in Princeton.

The temperature increase observed on the Soviet and English tokamaks during plasma compression along the minor radius was greater than expected from calculations. This was because the plasma interacted more weakly with the vacuum chamber walls and the diaphragm during the compression. As a result, the number of impurities entering the plasma, and hence the energy losses due to radiation, is smaller. Thus, the temperature was increased not only as a result of compression but also due to reduced losses.

In the experiments on the ATC, the plasma temperature was also increased by compression but less than expected. When the major radius of the plasma was decreased in these experiments, the plasma moved within the vacuum chamber. During this motion, the plasma has time to knock out very many impurity atoms from the cham-

ber's walls and the diaphragm. Their radiation drains energy from the plasma, and hence the plasma temperature at the end of compression turns out to be lower than the value predicted by the calculations.

In spite of the success of these experiments, especially on the Soviet and English devices, this method of plasma heating has not become widespread because it involves a considerable expenditure of energy for increasing the magnetic field.

Fast Atomic Beams

When we were discussing the difficulties of controlled fusion in Chap. 1, we found a paradox: the energy of the charged particles in a plasma with a temperature of 100 million degrees Kelvin (which is so difficult to attain by plasma heating) is only 10 keV. This means that a charged particle carrying an elementary charge will acquire as much energy by travelling between two electrodes across which a voltage of 10 kV is applied.

A voltage of 10 kV? But this can easily be obtained and such voltages are regularly used in laboratories. Even voltages of a hundred kilovolts have been obtained (not to speak of ten) which corresponds to a temperature of a thousand million degrees Kelvin. Thus, using acceleration in an electric field should yield even hotter particles

than those required for controlled fusion.

But how can they be used? It is as difficult for a charged particle to get into a good trap as it is to escape from it.

A way out was found by injecting neutral hydrogen atoms into a trap. Neutral hydrogen atoms freely pass through the magnetic field of the trap and once in the plasma, they are ionized and converted into H^+ ions which are confined by the magnetic field of the trap.

Since a hydrogen atom may pass through the magnetic field at any energy, there is no need to make this energy very high. It is sufficient, for example, to apply 20 or 30 keV, which is 2-3 times higher than the .energy corresponding to the fusion temperature of 100 million degrees Kelvin, in order to obtain an energy sufficient to compensate for the inevitable losses in energy.

A new problem then emerged, namely, how to accelerate neutral atoms to 20-30 keV. We know that an electric field, like a magnetic field, does not affect neutral particles.

Setting Up Charge Exchange

Charged H^+ ions can easily be accelerated and then converted via charge exchange into neutral H atoms, which can then be injected into a trap.

This idea was born at the beginning of the 1960s. The first H^+-ion sources to be used were originally designed for electromagnetic isotope separation. A natural mixture of isotopes was ionized by an electron beam. The formed ions were accelerated and then separated in a magnetic field.

The first injectors of hydrogen atom beams employed these ready-made H^+-ion sources. However, they turned out to be too weak for fusion devices, producing a current of the order of tenths of an ampere. At a voltage of 20-30 kV, the total power transferred by the particles of the beam was only a few kilowatts, which is naturally too low to heat a tokamak plasma noticeably.

The beginning of the 1970s marked a turning point in that plasma sources able to generate ion beams with large cross-sections were created. The plasma, which was rather cold from the fusion viewpoint (20-30 thousand degrees Kelvin) was produced by a gas discharge. In order to reduce the particle losses in the plasma, permanent magnets are mounted on the side walls of the discharge chamber. Thus the chamber is converted into a magnetic trap with a rather weak magnetic field, although strong enough to confine the cold plasma.

Electrodes with a large number of holes are arranged near the ends of the chamber and an accelerating voltage of the order of several tens of kilovolts is applied across

them. The electric field extracts the ions from the plasma, accelerating them as they pass between the electrodes, and injects them into the charge-exchange chamber.

The charge-exchange chamber is just a tube about 1 m long filled with hydrogen.

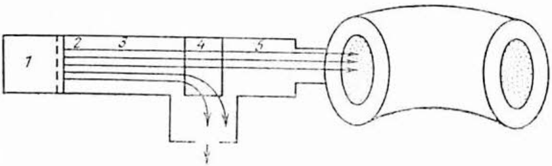


Fig. 6.5. Schematic diagram of neutral beam injector: *1*) ion source, *2*) anode, *3*) charge-exchange chamber, *4*) magnet, *5*) atom guide.

As a result of charge exchange, the accelerated ions are converted into neutral atoms, although some ions have no time to do so. In order to rid the beam of these particles, an electromagnet is placed at the outlet of the chamber which deflects the remaining charged ions from the beam. These particles are accumulated by a water-cooled collector (Fig. 6.5).

To prevent the gas from the charge-exchange chamber from getting into a tokamak, the formed atomic beam is passed through another tube, which has the fancy name of atom guide. The inner walls of this tube are coated by powdered titanium (in some devices, they are cooled by liquid

nitrogen or even helium). The powdered titanium greedily absorbs hydrogen. Therefore, the titanium-coated wall operates like a perfect pump, with an evacuation rate for the hydrogen of 10^5 l/s.

A beam purified in this way from ions and from the gas is then directed to a fusion device for plasma heating.

This design of injector produces a beam 20 cm in diameter. This beam of atoms, when accelerated to an energy of 40 keV, has an equivalent current of 25 A and the power transferred by the beam is a million watts.

Power Is Not All

The first attempts to employ atomic beams to heat the plasma in tokamaks were made at the beginning of the 1970s on the English Cleo tokamak. The beam power in these experiments was 140 kW. About 30% of this power, i.e. about 50 kW, were absorbed by the plasma. This power was considerably lower than that liberated in the plasma by the electric current. For this reason, even if the ion temperature was increased due to the additional heating power, the rise was so small that could not be clearly recorded. The only evidence that atoms from the beam were being ionized by the plasma and captured by the trap's magnetic field was the appearance of fast

particles in the spectrum of the atoms escaping from the trap as a result of charge exchange.

During the mid-1970s, heating experiments using neutral beams were started on several tokamaks, i.e. the Ormak and ATC American, T-11 Soviet, TFR French and Dite English tokamaks.

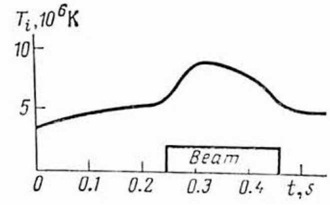


Fig. 6.6. Plasma heating by a beam of neutrals.

As a rule, the power of the injected atomic beam in these experiments was of the order of a few hundred kilowatts. However, the plasma was not eager to be heated. At the beginning of injection, the plasma temperature grew, which was followed by a vigorous increase in the impurity radiation. The plasma temperature stopped to grow and sometimes even decreased in spite of the fact that the heating was continued (Fig. 6.6).

Increasing the power of the injected beam did not help either because the greater the power, the less it affects the plasma temperature and at very large powers

it ceases to affect the temperature altogether (Fig. 6.7).

The reason for all this behaviour was the same, viz. radiation due to impurities.

The higher the energy input to the plasma, the more probable its contact with the

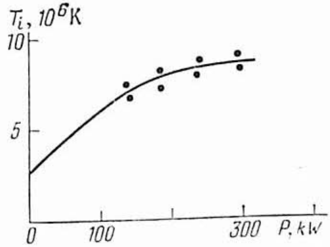


Fig. 6.7. Temperature to which ions are heated in a plasma as a function of the beam power.

wall, and hence the larger the amount of impurities, and hence the greater the energy drained away by their radiation. Unfortunately, the race was usually won by the impurities.

SHF-therapy of Plasmas

Another promising method for heating plasmas, viz. the use of high-frequency (HF) currents, was also worked out in parallel with the neutral atom method. Some readers may have experienced this method of heating as part of a physiotherapy treat-

ment, where HF currents are used to heat localized parts of the body.

In this method, the region of the patient's body to be heated is placed near a coil carrying high-frequency currents. From the point of view of physics, the coil acts as an antenna which emits radiowaves. These are then absorbed by the patient's tissues and their energy is liberated in the form of heat.

Since a plasma consists of charged particles, it interacts with radiowaves. A plasma can reflect, refract, or absorb radiowaves and all these properties can be used to heat it by radiowaves.

There are a few problems. First of all the plasma does not absorb all radiowaves, indeed. There are only a few isolated frequencies near which the absorption is noticeable. These isolated frequencies are associated with the rotation of the charged particles constituting the plasma (electrons and ions) in a magnetic field.

Electromagnetic waves, of which radiowaves are one sort. are essentially oscillating electric and magnetic fields. When an electron or an ion encounters the electric field of a radiowave, it is accelerated in it and its energy increases. But after half-period in the oscillations, the direction of the electric field is reversed, and the electron is decelerated. Therefore, a free charged particle simply oscillates under

the action of the radiowave, and no energy is absorbed.

If, however, the particle is also in a constant magnetic field, the energy of the radiowaves can be absorbed.

If the frequency of the radiowaves exactly equals the rotational frequency of the particle in the magnetic field, the situation

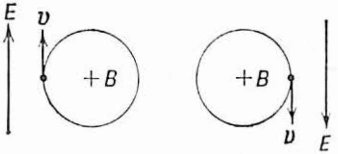


Fig. 6.8. Cyclotron resonance when the plasma is heated by radiowaves.

changes. Suppose the particle moves in a circle in the magnetic field and at a given instant of time is moving upwards (Fig. 6.8). If the field of the radiowave is also directed upwards, the positively charged particle will be accelerated and will gain energy. After another half-period of the rotation in the magnetic field, the particle will move downwards having described a half of the circle.

If the radiowave's frequency coincides with the rotational frequency of the particle, the electric field of the wave at this moment will also be directed downwards and the particle will be accelerated further.

The same thing will happen after the half-period when the particle will describe the second half of the circle, and the direction of the radiowave's field will be reversed.

This mechanism for accelerating particles in a magnetic field was discovered as far back as the 1930s and was used to accelerate particles in nuclear physics up to energies of millions of electronvolts, which is low from the modern point of view. This sort of accelerator is called a cyclotron and the technique of accelerating particles is correspondingly called cyclotron acceleration. Cyclotron acceleration is based on the coincidence of frequencies, i.e. the resonance between the radiowaves and the rotation of the particles in a magnetic field.

The rotational frequency of particles in a magnetic field depends on their mass, and hence it differs considerably for electrons and ions. For hydrogen ions in a magnetic field of a few teslas (which is normally used in magnetic traps), the rotational frequency is about several tens of megahertzs. This corresponds to the short-wave range, viz. wavelengths of about 10 m. The generation of radiowaves in this frequency range has been developed for the needs of radio communication. Therefore, it was not difficult to assemble a million-watt oscillator for ion cyclotron heating.

This situation is different for electrons.

The cyclotron frequency for electrons is about 10^4 MHz, which corresponds to millimetre wavelengths. This field of radio engineering was still at an early stage of development and although several oscillators generating millimetre-wavelength radiation had been invented, they were not powerful enough.

Work by Soviet scientists radically changed the situation.

At the Gorki Institute of Applied Physics of the USSR Academy of Sciences, several new oscillators, viz. gyrotrons, were developed. They can generate millimetre radiation at power of hundreds of kilowatts.

The first experiments on electron cyclotron plasma heating were carried out using these oscillators on the TM-4 and T-10 tokamaks. Twenty-four gyrotrons with a total power of 5 MW are planned for the electron cyclotron plasma heating in the T-15 tokamak.

Plasmas also absorb radiowaves at frequencies of hundreds of megahertzs. When radiowave energy is absorbed by the plasma in this region, the cyclotron rotation of electrons and plasma oscillations take part simultaneously. For this reason, these frequencies are called hybrid frequencies. They correspond to radiowaves in the metre range, which are widely used in television, and hence the construction of the appropriate oscillators is not a serious problem.

Even High Power Is Not Sufficient!

The first experiments on heating tokamak plasmas by radiowaves were started in the 1970s. The results of these experiments were not encouraging. Although the absorption of radiowaves was quite good, the plasma heating was poor, if any. A more detailed analysis revealed that the absorption occurs at the plasma periphery where the plasma density is low. When the radiofrequency power was switched on fast particles which had been accelerated in the field of the radiowaves appeared. However, these fast particles had no time to transfer their energy to the rest of the plasma. The large velocities of these particles create a large drift velocity in the nonuniform magnetic field of the trap. As a result, such particles soon reached the wall, carrying away their energy and, what is worse, generating a strong impurity inflow. Once they got into the plasma, these impurities started to radiate with such power that the bulk of the plasma was even cooled after switching on the radiofrequency oscillator instead of being heated.

In order to overcome this difficulty, great effort was spent on the design of the antennas. Ultimately, antennas for transferring HF power into the plasma bulk were developed for every frequency range. Now the fast particles that have been given high

energies by electromagnetic waves are confined much better. Most of their energy is transferred to other plasma particles raising their temperature. These improved antennas began to have some effect and the plasma started to be heated.

In experiments on plasma heating at hybrid frequencies on the FT-1 (USSR), ATC (USA), Petula (France) and JFT-2 (Japan) tokamaks, the plasma temperature was increased by 1-1.5 million degrees Kelvin at HF-oscillator powers ranging from 100 to 600 kW. This means that the temperature increment amounted to a few degrees Kelvin per watt. Hence it can easily be calculated that a power of the order of ten megawatts is required to attain the fusion temperature of 100 million degrees Kelvin. In these experiments, the plasma absorbed 75-90% of the supplied power, of which 15% went on heating the plasma, the remaining energy being carried away by the impurity radiation.

Nearly the same results were obtained during plasma heating experiments at frequencies corresponding to the ion cyclotron resonance. These experiments were carried out on the Soviet TM-1, TO-1 and T-4, and the American ST and ATC tokamaks.

At first, an attempt was made to heat ions at the rated cyclotron frequency of deuterium, but the heating was too weak. Later other frequencies were tried. Unexpect-

edly strong heating was obtained at twice the rated frequency for deuterium ions. The ion temperature jumped by 2 million degrees Kelvin for an oscillator power of just 150 kW.

In order to explain this astonishing success, prolonged and detailed investigations were required. Once again impurities were found "to be guilty"! Now ordinary hydrogen, of which the plasma contained some 2-3% along with deuterium, played the role of an impurity.

Hydrogen ions are half as massive as deuterium ions. Therefore, an oscillator frequency twice the cyclotron frequency for deuterium turned out to be the resonance frequency for hydrogen ions. The protons were effectively accelerated in the field of the wave and transferred their heat to the deuterium ions and electrons.

This method of heating proved to be very effective. Measurements on the Soviet T-4 tokamak showed that only the hydrogen ions were accelerated to large energies, while the deuterium ions, which constitute the bulk of the plasma, were not accelerated to high energies, and hence they continued to be well confined.

This method of heating is likely to be even more effective with larger devices. The results of the first experiments on the TFR (France) and PLT (USA) tokamaks apparently confirm this. The increment in the

ion temperature was about 20 degrees Kelvin per watt, which means that the fusion temperature can be attained with an oscillator having a power of only 5 MW. However, the behaviour of impurities at this level of input power is not yet known. Even in recent experiments at powers one tenth this value, impurities carry away more than half the input power. Indeed, everything rests on impurities.

Divertor

Since impurities arrive in the plasma from outside, they first enter its outermost layer. To overcome the impurity inflow, they should be continuously removed from this layer. This idea formed the basis of the device proposed by L. Spitzer in 1951 and called a divertor. This device was described in Chap. 4 as applied to stellarator. Later, divertors were employed in tokamaks. Various divertors differing in their magnetic field configurations were developed in the tokamak programme, but they work in the same way.

Using a special magnetic winding, the outer layer of the plasma several centimetres thick (the divertor layer) is split off from the plasma column and directed into another chamber where the plasma and its impurities are converted into a gas and pumped out.

The Spitzer divertor is known as a toroidal divertor (Fig. 6.9*b*). This, of course, is not the only design. A divertor layer can be formed in a different way if a current is passed through a wire laid along the outer

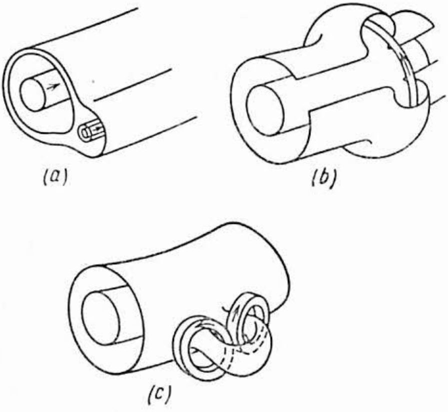


Fig. 6.9. Different types of divertor: (*a*) poloidal, (*b*) toroidal, and (*c*) bundle divertor.

surface of the torus. Then the loop of magnetic field lines is formed in the transverse (poloidal) direction (Fig. 6.9*a*). For this reason, this sort of divertor is termed poloidal.

In both designs, the divertor layer is skinned off from the whole of the surface of the plasma. However, by using the rotation of magnetic field lines, we can save space

and install a small local divertor which splits off a layer of field lines in only a small region (Fig. 6.9*c*). Due to the rotation of the field lines, the plasma particles which have travelled around the torus many times ultimately find themselves on the lines passing through the divertor. A local divertor of this sort was used on the English Dite tokamak. It was called a bundle divertor.

Experiments with a poloidal divertor were carried out on the Diva tokamak in Japan and the T-12 tokamak in the USSR. These experiments showed that poloidal and bundle divertors have nearly the same effect, namely, the impurity inflow to the plasma is reduced by about half.

Chapter 7

60 Million Degrees Kelvin in a Tokamak

By the end of the 1970s, the tokamak experiments revealed that the potential of heating by plasma current was practically exhausted. Thoroughly cleaning the chamber's walls, utilizing divertors, and meticulously selecting the discharge conditions had made it possible to raise the electron temperature to 15-20 million degrees Kelvin, and the ion temperature to 10 million degrees Kelvin.

In order to proceed, additional methods of plasma heating were required. Experiments with the additional heating methods described in the previous chapter at power levels of hundreds of kilowatts revealed that the two most promising directions were heating using high-frequency fields at frequencies corresponding to the ion and electron cyclotron resonances, and heating with the help of beams of fast neutral atoms. The results of the first experiments indicated that the fusion temperature could be reached with these techniques at powers of millions of watts.

Devices intended to operate at such a power are quite complicated. Their design and construction require the solution of a whole range of technical problems and is a time-consuming process. Significant achievements were made towards the end of the 1970s in the USSR in the development of gyrotrons, the centimetre-range high-frequency oscillators.

American scientists at Oak Ridge set the pace in developing the technology for obtaining neutral beams of a megawatt power. Injectors with a beam power up to 0.9 MW were developed early in 1978. Four such injectors were prepared for experiments on the PLT (Princeton Large Torus), a giant American tokamak.

The following technique was used on the PLT for plasma heating. As usual, a plasma discharge was first created, and the plasma was then heated by passing a current through it. The ion temperature was raised to 10 million degrees Kelvin in this way. Beams of fast hydrogen atoms were directed into the plasma to heat it still further.

The author of this book together with V.A. Vershkov of the Kurchatov Institute of Atomic Energy participated in experiments on the diffusion of impurities in the tokamak plasma at Princeton and witnessed plasma heating in the PLT.

Problems and Troubles

The Princeton experiment was not initially very successful. The four atomic beam generators could rarely be made to operate synchronously. Hence the power of the beam in each pulse, or shot as the specialists call it, varied very unexpectedly. Even when the generators operated synchronously, the plasma would still not heat up. Fast particles hitting the chamber's walls were knocking out atoms of iron and tungsten from the walls and also atoms of oxygen and carbon which had apparently been adsorbed on the walls. These atoms started to glow brightly as soon as they entered the plasma, thus cooling it by carrying away energy. Tungsten was the main source of trouble. In spite of the strong magnetic field, tungsten ions mysteriously managed to reach the centre of the plasma cluster in a few milliseconds and started radiating energy. The tungsten radiation power was so high that it often exceeded the total power supplied to the plasma by the current and atomic beams. Physicists gloomily joked that a patent should be obtained for the method of plasma cooling, should there ever be a need to rapidly cool a reactor.

Having suffered thus for about two weeks, the scientists realized that tungsten was the root cause of all the problems. It was decided to open the reactor and get rid of all the

tungsten parts and replace them by stainless steel components.

When the experiments were resumed, it was found that iron became the predominant impurity, but less total power was emitted by the plasma than was supplied to it by the beam. Consequently, the plasma was heated to some extent. After several shots, the ion temperature increased from 10 to 15, or even to 20 million degrees Kelvin.

Naturally, the success had to be sealed by attempting to change the material in the components in direct contact with the plasma. The fewer electrons per atom the material had, the better. Hence, turning to the elements at the beginning of the Periodic Table, the scientists decided to replace the iron with carbon or, more precisely, with graphite since diamonds whose size is tens of centimetres cannot be obtained.

The resumption of the experiment was eagerly awaited. What temperature would the plasma now attain?

The carbon construction was found to be much better than the iron one. The power of plasma radiation was sharply reduced, and the temperature rose.

Incredible!

The temperature did not just rise, it soared! When all four beams operated synchronously, the temperature rose to infinity.

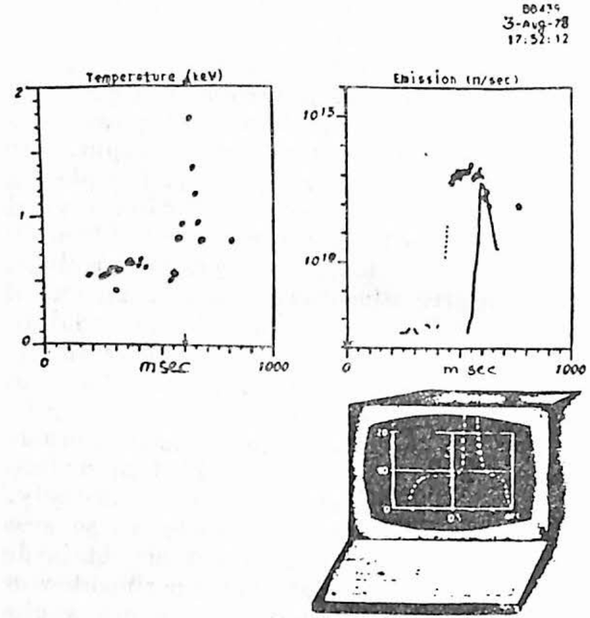


Fig. 7.1. This display was given by the computer on 3 August, 1978, at 17 hr 52 min 12 s after the shot which suddenly raised the ion temperature. The digits *1* and *2* correspond to temperatures of 10 and 20 million degrees Kelvin. Time is plotted along the abscissa. The figure 1000 corresponds to 1 s. The same screen also displays the creation of neutrons in a fusion reaction. In this shot, the rate of neutron generation grew to 10^{13} particles per second. The display exhibited this phenomenon as shown. The actual temperature attained in shot No. 68 439 could not be ascertained because the point went beyond the screen.

At least that is what the detector display reported. Figure 7.1 shows the computer report immediately after the shot. The ion temperature was calculated from the rate of neutron generation, i.e. from the rate of the fusion reaction itself. We have said that this temperature is close to 10 million degrees Kelvin if no additional measures for heating are undertaken. The beams were expected to raise the temperature. The computer was programmed to scale the temperature so that 20 million degrees Kelvin was the maximum temperature. However, when the beams were switched on, the temperature curve shot upwards, crossed the top limit and went beyond the edge of the screen.

One of the scientists observing the pattern exclaimed: "Something strange is happening to the plasma!" After a brief discussion, all the scientists agreed that, on the contrary, the plasma was behaving normally for once: its temperature rose in accordance with the simplest law, viz. in direct proportion to the power being supplied.

In the course of their tiresome fussing with the tricky plasma, the physicists had somehow abandoned the idea that even such simple laws are obeyed in nature. After all, it took scientists more than a quarter of a century to attain a temperature of 10 million degrees Kelvin. Then it was found that nature had prepared a surprise

for them: it was possible to heat a plasma almost as easily as water in a kettle.

Although there was no dearth of gloomy theoretical predictions about the instabilities that must appear in a tokamak plasma at a temperature of tens of million degrees, this turned out to be a rare case in which the plasma behaved better than expected.

Record Set at Night

The plasma temperature rose briskly. With increasing power, temperatures of 50, 60 or even 70 million degrees Kelvin were recorded. The general excitement reached a peak and the physicists burnt midnight oil to deepen their knowledge of plasma.

A disturbing thought suddenly emerged amidst all this euphoria. What if there was some mistake in the temperature detection? After all, no measuring instruments had ever been used at these temperatures. Everything had to be verified several times, fresh calibrations were required, and a series of test experiments had to be performed before it could be asserted that the temperature was being correctly measured.

Meanwhile, the temperature was indeed approaching the fusion level. The neutron generation rate reached 7×10^{13} particles per second and the technicians measuring the radiation in the control room of the PLT warned that further work would be

impossible without improving the shielding from the neutrons since the radiation had already reached the maximum admissible levels.

Even the theorists working in offices adjoining the PLT announced with solemnity that a neutron defect was appearing in their formulas.

The experimental results continued to be discussed in the mean time. As a precautionary measure, the estimated temperature values were lowered by taking into account all the possible corrections. On the other hand, any correction that increased the estimated value was viewed with scepticism. The discussions would probably have continued till the end of the August, when the International Conference on Plasma Physics and Controlled Nuclear Fusion Research was to be held at Innsbruck in Austria. However, an end was put to all discussion in the middle of August by events worthy of a crime thriller.

On the night of 10 August, 1978, when the highest plasma temperature was reached, the instruments registered 85 million degrees Kelvin. One scientist, an Italian, could not hold his excitement and telephoned his colleagues in Italy, who were also working on the same problem at the Plasma Physics Laboratory at Frascati near Rome, of this sensational result.

Early next morning, there was a call to

the Princeton laboratory from Washington. Quoting information from Italy, the authorities demanded to know about the sensational discovery made at the PLT. Since the results had been obtained late at night, the head of the PLT project, W. Stodiek, knew nothing about them. He rushed furiously to the laboratory and reprimanded his scientists for revealing unconfirmed results, since they should be verified many times before they could be believed.

On the same day, an order prohibiting the release of unpublished results was issued at the laboratory and everyone working on the project was made to sign it, thus pledging silence. It was too late! Rumours had spread everywhere and reporters practically laid siege to the Princeton laboratory. After three days, the laboratory capitulated, and reporters were allowed to see the PLT. A temperature of 60 million degrees Kelvin was cautiously reported to have been attained, although the instruments showed that 85 million degrees Kelvin had been reached in several shots. A decrease of 15 million degrees was due to legitimate corrections, while another 10 million degrees were knocked off the recorded value simply out of caution. After all, a temperature of 60 million degrees had been reached dozens of times, while 85 million degrees had only been attained in a few shots

At a celebration held on the same day, five huge cakes with "Ion temperature 60 million degrees" in icing were consumed.

What Next?

The results obtained on the PLT raised the hopes that the problem of controlled fusion will be solved after all. Two important experimental results made the scientists confident. First, the plasma temperature had been raised to about 100 million degrees Kelvin. Second, in spite of the theoretical predictions, nothing unusual happened to the plasma as it approached the fusion temperature.

These conclusions are very important, but it would be wrong to assume (as some newspapers erroneuosly reported) that the problem of controlled nuclear fusion had been solved. After all, heating a plasma to the desired temperature is just one of the three necessary conditions. The temperature must be maintained in a plasma with a density of $2 \times 10^{20}\ m^{-3}$ for at least one second. The PLT results on the last two factors were quite modest: the plasma density at the record temperature was just 1/10th of the required value, and the confinement time was 1/40th of a second. A lot of work still had to be done (Fig. 7.2).

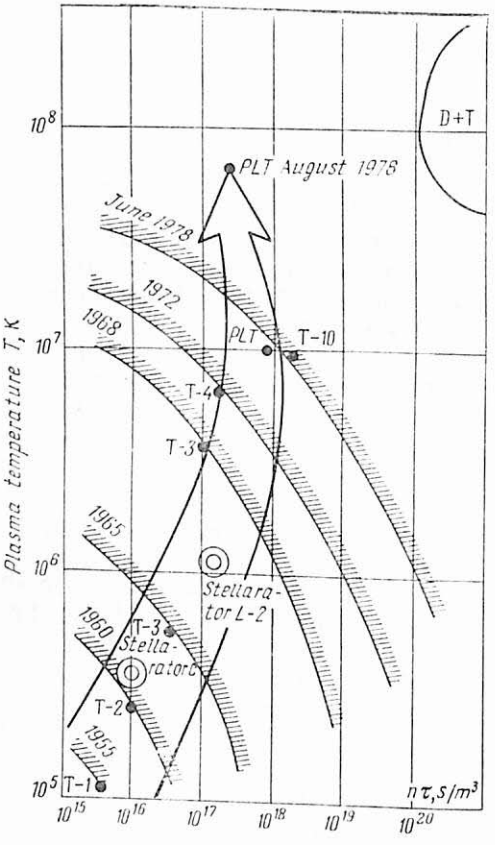


Fig. 7.2. Showing the breakthrough of the PLT on the battlefield map.

Attack on a Wide Front

Tokamak investigations are at the centre of attention of scientists all over the world who are working on controlled nuclear fusion.

Investigations along a very broad front are being pursued in the USSR. There are still many obstacles on the path towards the first thermonuclear power plant and so there is plenty of work for everybody in the field.

The largest Soviet tokamak, the T-10, is being used at present to study the laws of plasma confinement under various operating conditions (Fig. 7.3). In order to predict the plasma behaviour in a fusion reactor, it is necessary to find out how confinement characteristics depend on density, temperature, and magnetic field. It is especially important to find how the thermal conductivity and the particle confinement time of the plasma itself vary.

Experiments carried out over the last few years show that the confinement of both the particles and the plasma energy in a tokamak improves with increasing plasma density. Hence the reactor of the future must have the highest possible plasma density. But an increase in the plasma density also means an increase in its pressure.

Of course, we can increase the magnetic induction as well, but this requires the ex-

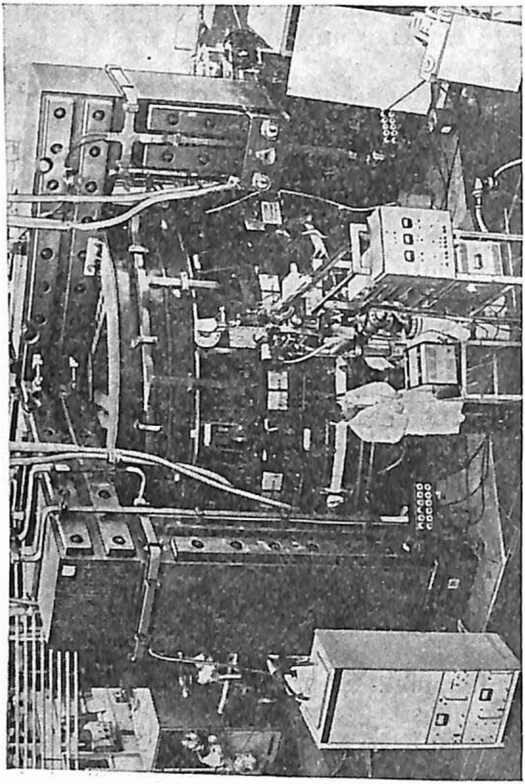


Fig. 7.3. T-10 tokamak.

penditure of large amounts of energy. Hence it is desirable to attain the largest possible value of the ratio β of the plasma pressure to the pressure of the magnetic field. This quantity is very important for the economic operation of a fusion reactor. Preliminary estimates showed that the creation of a viable fusion reactor is only possible if β is at least 5 or 10%.

In modern tokamaks, the value of β is usually about 1%. Increasing the plasma pressure is not a simple matter. Theorists predict a number of severe instabilities that might appear in a plasma when its pressure is increased. Fortunately, these gloomy predictions have not always been confirmed by experiment. For example, the plasma pressure in the T-11 tokamak was brought to about 2.5% of the magnetic field's pressure by additional heating the plasma with neutral atom beams. The theorists were forced to search the reasons behind this unexpected plasma stability.

A method for plasma heating by radiowaves is being worked out on the T-10 tokamak. Experiments are being carried out with a wavelength of 3.6 mm at which the frequency of the radiowaves is equal to the rotational frequency of the electrons in the magnetic field. Under these conditions, the electrons absorb the energy of the radiowaves and then transfer it to the ions. Recently, the electron temperature in these

experiments was raised to 30 million degrees Kelvin for a plasma density of $(4\text{-}5) \times 10^{19} m^{-3}$. The generator used in these experiments had a power of just 0.5 MW. Hence the heating efficiency in this experiment was higher than that of the plasma heating by neutral beams on the PLT.

Soviet and Czechoslovakian scientists working together on the T-7 tokamak have set themselves the task of exciting a current in the tokamak plasma using high-frequency waves. This effect may have far-reaching consequences for the entire tokamak programme. For the traditional induction method of exciting current in a tokamak, the duration of the current pulse is always limited since the induction voltage appears only as a result of a continuous increase in the magnetic flux inside the plasma loop and the magnetic flux cannot be indefinitely raised because of the magnetic saturation of the iron in the transformer or because of the limited thermal or mechanical strength of the winding. Hence a tokamak will have to be designed to operate intermittently in pulses each having a duration of a few hundred to a few thousand seconds. In the interval between the pulses, the current is switched off and the plasma perishes. Apart from the necessity of creating and heating the plasma anew after each pulse, a number of technical problems

are associated with this method because of the effect of the pulsed thermal and mechanical loading on the strength and durability of the structural components. Hence a tokamak reactor that could run at steady state would automatically eliminate one of main drawbacks.

Besides significantly increasing the plasma temperature in the T-7 tokamak, the scientists also observed a decrease in the voltage needed to make the current flow through the plasma. At first it was assumed that the decrease in the voltage was due to a drop in the electric resistance of the plasma, since the electron temperature increases and the plasma's resistance decreases in proportion to $T^{-3/2}$ with an increase in the electron temperature. Accurate measurements and calculations revealed, however, that this was not the only factor responsible for the voltage drop. It was also due to the appearance of an additional current in the plasma as a result of the direct action of a high-frequency wave on the plasma electrons.

The generator used in these experiments had a power of about 200 kW. During the pulse of the radiofrequency oscillator, the voltage across the plasma loop dropped to zero and the current was only sustained by HF field. The current in the experiment was over 200 kA. This means that a current of several million amperes, which is what

is required for plasma confinement in a tokamak reactor, could be produced with the help of radiofrequency generators. Thus, a tokamak reactor operating under steady-state conditions is a possibility.

At the Physico-Technical Institute in Leningrad, the Tuman-2 and Tuman-3 tokamaks are being used to study the plasma heating during compression. The plasma is produced in these reactors under a relatively weak magnetic field, and then the field is abruptly increased. The pressure of the magnetic field compresses the plasma, which is thus heated strongly.

Another useful effect was discovered in these tokamaks. During compression, the plasma is moved a considerable distance from the walls of the vacuum chamber. This considerably reduces the number of impurities entering the plasma and so reduces the heat losses.

In order to utilize the advantages of this method, a new device called T-14 has been designed. In this unit, the plasma will be compressed by rapidly increasing the magnetic field in the coils. Calculations show that the temperature and density of the plasma must increase to the fusion level in this case.

A block diagram of the unit is shown in Fig. 7.4. A huge torus 11 m in diameter along the axis with coils 4 m in diameter serves as an accumulator of energy. About

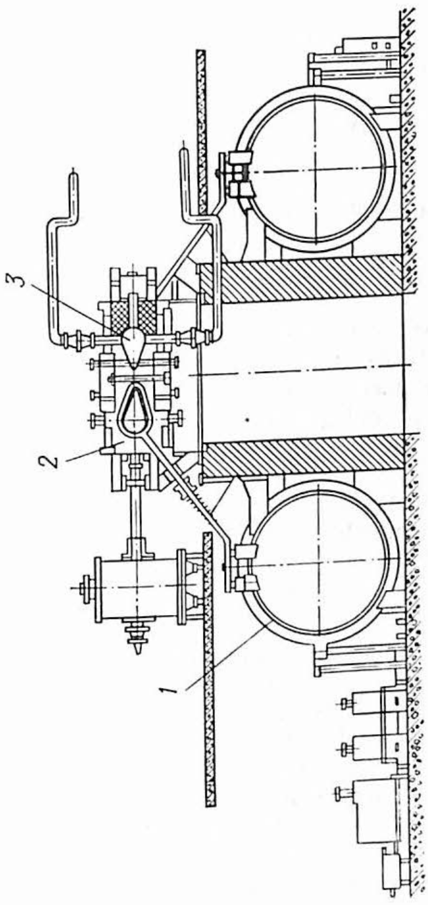


Fig. 7.4. T-14 tokamak design: *1*) inductive accumulator of energy, *2*) tokamak coils, *3*) plasma.

15×10^7 J of energy can be stored in it in the form of the magnetic field energy. All this energy is fed into the massive and strong (upper) coils of the tokamak. The electric power in the tokamak attains values up to 10^7 kW, which is even more than the power of a prospective fusion reactor. For a power supply of this magnitude, the magnetic field in the plasma reaches 13 T and the plasma reaches a temperature at which the fusion reaction can take place.

The plasma is first heated by injecting neutral atoms and by radiowaves. Two prototypes have been constructed, namely, a 1:10 model of the magnet of the T-14 tokamak, and the experimental T-13 unit.

The prototype of the magnetic unit is used for strength tests because a magnetic field of 20 T exerts a pressure of 1600 atm and it comes on too suddenly, in the form of a shock. It is not an easy task to produce a magnetic winding capable of withstanding shocks of this magnitude.

In the T-13 tokamak, the magnetic field may reach 1.7 T during plasma compression which is carried out simultaneously along the major and minor radii of the torus. The shape of the plasma's cross-section can be modified by using additional windings, and can be made circular or elongated along the vertical. Theorists predict

that the plasma's stability must be worse in the latter case during compression.

The highest hopes of attaining the cherished goal of producing a plasma with fusion parameters are being pinned on the T-15, the largest tokamak to be designed and constructed in the USSR.

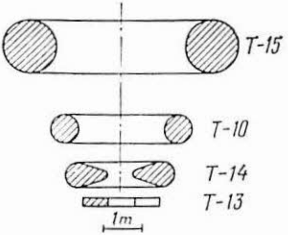


Fig. 7.5. Comparison of plasma size in Soviet tokamaks.

This will indeed be a giant reactor with a plasma volume of 23 m^3. The major radius of the torus will be 2.4 m and the plasma will have a radius of 0.7 m. A superconducting magnetic system will be employed and the experience gained on the T-7 tokamak will be put to use. The magnetic induction will be as high as 5.0 T and a current of 2 MA will be passed for preliminary heating and confinement of plasma. The plasma will then be heated and temperature raised to initiate a fusion reaction by fast atomic beams of power 10 MW. Another 4 MW will be added by radiowaves.

Figure 7.5 shows how efficient the new T-15 tokamak will be as compared to those existing. This figure shows a section of plasma in the new Soviet T-13, T-14 and T-15 tokamaks and in the largest existing tokamak, the T-10, for the sake of comparison.

Naturally, such large reactors take a long time to build. Impatient young scientists at the Kurchatov Institute of Atomic Energy have composed a jocular song advocating the construction of the T-34 straight away for rapid progress: "It has never let us down!" (Incidentally, T-34 was the main Soviet tank in the Second World War.)

Chapter 8

The Renaissance of Stellarators

It Still Does Not Work. Why?

Let us now return to 1969, where we left stellarators in fairly hard times.

The failure of the American stellarator C put pressure on the stellarator research in other countries as well. The low plasma temperature and gloomy predictions concerning the confinement time at fusion temperatures appeared even more dismal when viewed against the triumphs of the tokamaks.

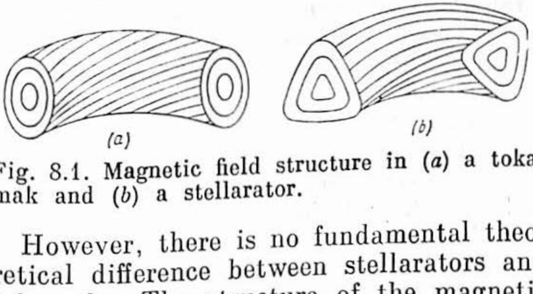


Fig. 8.1. Magnetic field structure in (*a*) a tokamak and (*b*) a stellarator.

However, there is no fundamental theoretical difference between stellarators and tokamaks. The structure of the magnetic field confining the plasma is essentially the same in both cases: the magnetic field lines move helically around the torus forming closed nested magnetic surfaces (Fig. 8.1).

However, the merits of the theory notwithstanding, experiment is always decisive. The attention of the organizers of fusion research all over the world was focussed on tokamaks and a cold wind blew over stellarator research.

The stellarator programme continued, but only due to the tenacity of some individuals. A leading role in the rescue was played by Prof. M.S. Rabinovich, a Soviet scientist and the head of the Plasma Physics Laboratory at the Lebedev Physical Institute of the USSR Academy of Sciences. Investigations on the L-1 stellarator were not discontinued at this laboratory.

Armed with the theory and the results of experiments carried out on the small stellarators, the German Wendelstein-2 and the Soviet L-1 stellarator, he exhorted his colleagues in the USSR and abroad not to discontinue research but to try to find out why the American stellarator had failed to progress in the field.

The courage and determination of Prof. Rabinovich and the foresight of Academician L.A. Artsimovich, the head of the Soviet fusion programme, ensured the continuation of stellarator research in the USSR.

The reputation of the Soviet research activity helped scientists in the UK and the FRG to defend their stellarator programmes.

To understand the reasons behind the poor confinement of the plasma, it was necessary

to study the structure of the confining magnetic field. The structure of the magnetic surfaces in stellarators was carefully studied and an unexpected result was obtained. It was found that the usual pattern of magnetic nested surfaces enclosing each other with increasing rotation angles of the field lines (see Fig. 8.1) only exists if the stellarator is not subjected to any external perturbing fields. The perturbing fields, however, are produced quite easily. They are formed by the slightest imperfection in the windings that produce the stellarator magnetic field, or by any stray magnetic fields, for example, by the transformer field that induces the current in the plasma.

The structure of the stellarator magnetic field was found to be extremely sensitive to perturbing fields, especially where the field lines end at the same point after a few circles and are thus closed.

If the perturbing field disturbs such a line even slightly, it no longer returns to the same point but continues and the structure of the magnetic surfaces changes considerably. Magnetic islands are formed instead of a magnetic surface (Fig. 8.2).

The field lines deviate considerably from the initial magnetic surface outwards and inwards. This is very bad for the confinement of charged particles in the plasma. When a charged particle hits such a line, it appears on the outer side of the magnetic

surface after a few cycles and gets quite close to the wall of the vacuum chamber. If the charged particle collides with another charged particle at this stage, it can easily cross to the line of force of another magnetic surface and thus move further outwards.

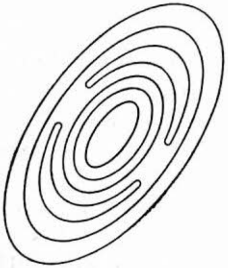


Fig. 8.2. Formation of "islands" in the stellarator's magnetic field structure near a magnetic surface for which the rotation angle of the induction lines is $i \to 1/2$.

Islands begin to form on the magnetic surface even when the perturbing fields are a thousand times weaker than the main magnetic field. This means that all the components and especially the magnetic winding of the stellarator must be prepared with extreme care and precision. Even an error of 10^{-4} may turn out to be disastrous.

Nobody foresaw the need for such high precision when the stellarators were being

constructed and so the accuracy common in heavy engineering was adopted.

Hence it is not surprising that the magnetic windings of the first stellarators had errors and departures from the nominal behaviour. These errors considerably distorted the structure of magnetic surfaces in them. Thus the reason for the poor plasma confinement in stellarators in general and in the American stellarator C in particular was finally uncovered. To rectify the error, compensating windings were added to the Soviet TOR-2 stellarator. The magnitude and direction of the magnetic field produced by these windings should be such that the undesired perturbing fields due to imperfections on the windings generating the main field were completely neutralized. This was somewhat successful and the plasma confinement time in the stellarator was increased slightly.

Better to Stitch Anew Than to Sow On Patches!

Naturally, it was quite difficult to get rid of all the errors and inaccuracies of the magnetic field. Therefore, it was decided to construct a new stellarator with a high degree of precision from scratch.

Life Is No Easier for Electrical Engineers Than It Is for Physicists

A good stellarator turned out to be very difficult to build with its complex helical winding and requirements on the construction much more stringent than in ordinary engineering. Besides, the project was to construct a single experimental setup.

Finally, the physicists took upon themselves the task of preparing the helical winding and the new-generation stellarator was commissioned in 1975 at the Lebedev Physical Institute of the USSR Academy of Sciences (Fig. 8.3).

The device was called the L-2 stellarator. The new stellarator had quite modest dimensions: the major radius of the torus was 1 m, the vacuum chamber had a diameter of 35 cm, and the magnetic surfaces for plasma confinement were elliptical. The size of the ellipse was 28×16 cm, so that its cross-sectional area was equal to that of a circle with radius 11.5 cm.

The ill-fated stellarator C was nearly the same size, but the helical winding of the L-2 was prepared with a much higher degree of accuracy. The quality of the magnetic surfaces was carefully controlled with the help of electron beams, and all flaws and drawbacks in the adjustment of the magnetic system were eliminated.

At about the same time, new-generation

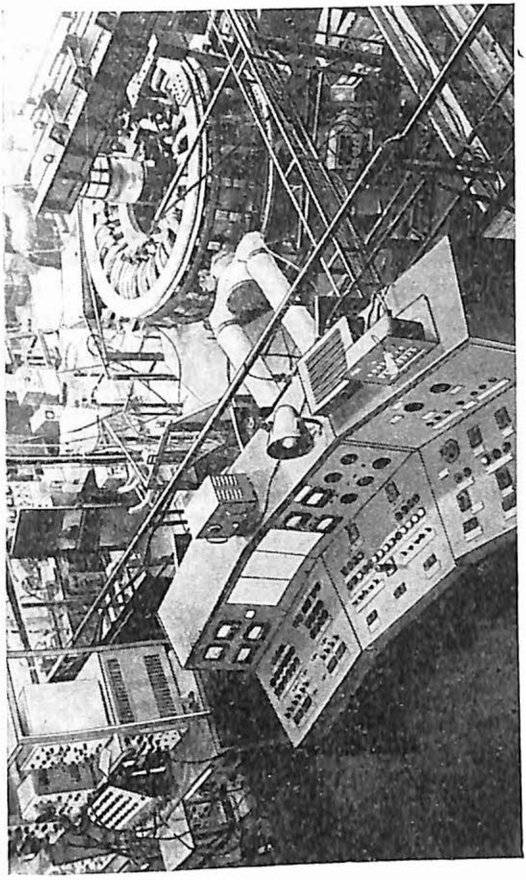


Fig. 8.3. L-2 stellarator.

stellarators were built in the UK (Cleo) and the FRG (Wendelstein-7A). All three units were ready for operation at nearly the same time and experiments began in 1975.

The plasma was produced and heated in all three units with an electric current. This current had to be restricted to about 20-30 kA in order to prevent the stellarator field structure from being distorted by the emerging magnetic field. This is a very low current for a unit of such magnitude. Tokamaks of a corresponding size have a current of 100-200 kA flowing through them.

Nevertheless, the plasma heating by the current was found to be considerable, and the plasma temperature easily rose to a few million degrees Kelvin. The plasma temperature in the stellarators rose to the temperature of the plasma in tokamaks but with much lower heating powers. The inevitable conclusion is that energy losses in stellarators are much lower than those in tokamaks.

This result was obtained almost simultaneously at all three units in the USSR, UK, and FRG, and reported at the next International Conference in Berchtesgaden (FRG) in 1976. Two years later, at the Innsbruck conference, detailed information was supplied, thus enabling a comparison of plasma confinement parameters in tokamaks and stellarators.

By that time, the dependence of the plasma lifetime on various parameters had been studied quite extensively for tokamaks. The experience gained in these studies was generalized into empirical formu-

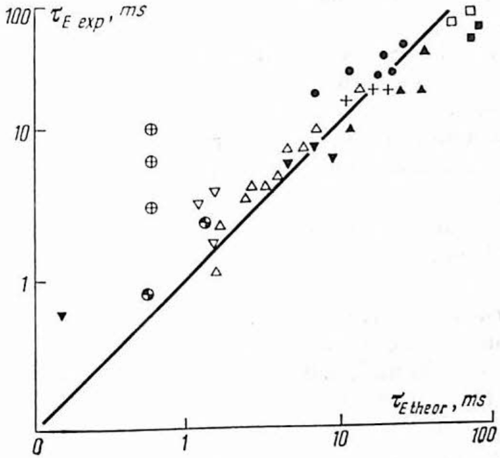


Fig. 8.4. Energy time predicted by Mirnov's formula (abscissa axis) vs. the experimental value (ordinate axis) for various tokamaks and the L-2 stellarator (⊕).

las, which took into account the influence of the magnetic field, plasma size, plasma density, etc. The results of calculations of the plasma lifetime according to one of these formulas, proposed by the Soviet physicist S.V. Mirnov, are shown in Fig. 8.4. Mirnov's formula provides a quite

accurate description of the energy lifetime as a function of the most important parameters for most tokamaks. This can be seen because the experimental points for the tokamaks lie close to the straight line predicted by Mirnov's formula (see Fig. 8.4.).

In the same figure, the circles with crosses show the confinement times for the plasma energy in the L-2 stellarator.

A comparison of the results shows that the confinement time in stellarators is much larger than the value expected for tokamaks. For the plasma and magnetic field parameters used in the L-2 stellarator, the energy confinement time given by Mirnov's formula is less than 0.001 s. This was confirmed by experiments on the TM-3 tokamak using the same parameters. In the L-2 stellarator, the energy confinement time was found to be three times, and in some cases even ten times, longer than this value.

When a Stellarator Works As a Stellarator

Although plasma heating by an electric current requires much simpler equipment than the equipment needed by other heating methods, this technique is not very suitable for stellarators. This is so because the magnetic field produced by the current distorts the stellarator field and deteriorates the

plasma confinement. Figure 8.5 shows the decrease in the energy confinement time in stellarators with increasing current. However, we can look at the same graph from a different point of view: it shows that

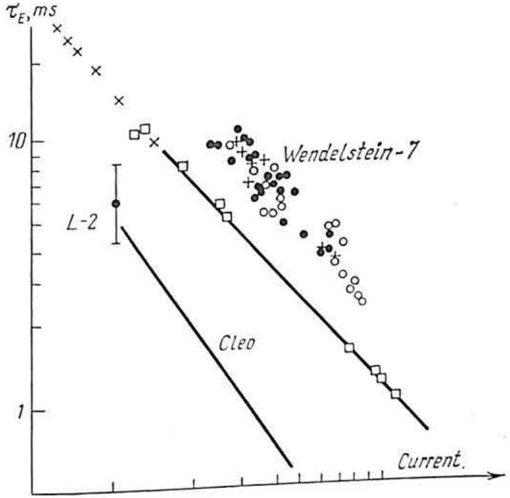


Fig. 8.5. Plasma confinement time vs. current.

the plasma confinement time in stellarators can be increased rapidly by decreasing the current. What will happen if the current is switched off completely?

The plasma must be heated somehow. Hence, before switching off the current, we must find a way to heat the plasma

without a current. Since the structures of the magnetic fields in tokamaks and stellarators are nearly identical the plasma in a stellarator can be heated using the same methods as in tokamaks.

The first attempt to obtain a currentless plasma in a stellarator was made by English scientists on the Cleo. Instead of current, they used a 15-kW radiowave generator, operating at the electron cyclotron resonance frequency to heat the plasma.

In principle, the experiment was a success. The current was switched off and the plasma survived in the trap and was only sustained by the energy of the radiowaves. For a generator of such a low power, the plasma temperature came to steady state at the rather low value of 600 000 degrees Kelvin, but it did not drop to zero.

More impressive results on plasma heating by radiowaves were obtained by Japanese scientists at the Heliotron-E stellarator using a generator with a power of 200 kW, and, accordingly, the electron temperature was much higher (five million degrees Kelvin).

Physicists at the Physico-Technical Institute at Kharkov used a different technique. They set up an experiment with the Uragan-2 stellarator on plasma heating by radiowaves that were in resonance with ions rather than electrons. The experiments on the Uragan-2 were not aimed at

obtaining a currentless plasma. The ions were heated, however, quite well, and an ion temperature of four million degrees Kelvin was attained. This is four times the temperature reached using a current without radiowaves.

The first experiments on plasma heating by neutral atomic beams were carried out on the German Wendelstein-7A stellarator in which no special provisions had been made for introducing atomic beams. Hence the German physicists had to inject the atomic beams nearly at right angles to the plasma (to be more precise, at an angle of 84°).

The beam had therefore to traverse a short path of just about 20 cm in the plasma. The plasma density must be very high ($n \gtrsim 10^{20}\ \mathrm{m}^{-3}$) to enable the atoms in the beam to collide with plasma particles. This is the same density that the plasma is likely to have in a future fusion reactor.

It is very difficult to attain such a plasma density in the comparatively small modern reactors. A remarkable property of stellarators, viz. their stability to disruption, has played a very important role in solving this problem. It would not have been possible to attain such a density in a tokamak under similar conditions.

The required plasma density was obtained in the Wendelstein-7A stellarator by passing an electric current through it.

This plasma served as the target for a 27 keV beam of neutral atoms. Four such beams were used and their total power exceeded 1000 kW. However, only about 30% of the beam energy is liberated in the plasma. Most of the fast atoms fly right through the plasma without colliding once with plasma particles.

Whatever the case, the plasma did get heated, and it was heated very well! The temperature of the plasma's ions increased right up to seven million degrees Kelvin.

Armed with such a powerful heating source, the German scientists naturally tried to switch off the electric current through the plasma that was used to produce the plasma before introducing the beams. As the plasma current was decreased, the current in the helical winding of the stellarator was increased so that the resultant rotation angle was always larger than 1/2. The plasma remained stable and the current was brought down nearly to zero. True, the current could not be reduced to zero altogether, which is quite interesting. It was found that when a plasma is confined in a stellarator, a current appears automatically in it even if no external voltage is supplied to the plasma. The spontaneous current in the Wendelstein-7A stellarator had a value of 1000 A.

Thus, a currentless mode of plasma confinement is possible in a stellarator. And

with remarkable effects! The plasma confinement time increased sharply. It increased to such extent that it was difficult to measure it, because the beams of neutral atoms did not work long enough. In any case, it was many times longer than when a current was passed through the plasma.

But a price has to be paid for everything. This long particle confinement time in the stellarator created new problems.

Impurities started accumulating at the centre of the plasma column, where the temperature is the highest. The impurities cooled the plasma by radiation and so effectively that the plasma temperature at the centre of the column started falling at a certain instant in spite of the continued injection of the atomic beams. These impurities turned out to be oxygen. Oxygen ions seemed to appear in the hydrogen beams during the production and acceleration of the hydrogen ions. Some of the oxygen ions then exchange charges with the hydrogen ions and enter the plasma. Owing to a long particle confinement time in a currentless stellarator, the oxygen ions entering the plasma with the beam accumulate in the plasma and cause the radiation losses. Further experiments are needed to solve the problem. Meanwhile, physicists working on the stellarator programme must be congratulated on having reached such a milestone. According to some estimates,

the energy confinement time in a currentless stellarator has reached a value of 0.035 s at a density $n = 10^{20}\ m^{-3}$, viz. the plasma density in a future fusion reactor. The product $n\tau$ has already attained values of about $3.5 \times 10^{18}\ s/m^3$, which is only 1/30th

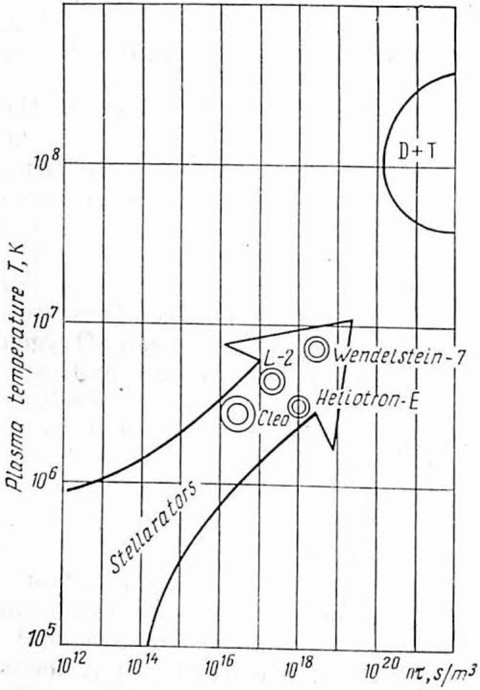


Fig. 8.6. A breakthrough in the value of $n\tau$ to nearly fusion level marks the triumph of the stellarators.

of the value required for a fusion reactor. All this has been made possible in units with a plasma radius of just 10 cm (Fig. 8.6).

Since the lifetime increases with the square of the plasma radius, Lawson's criterion will be satisfied for a plasma radius of 60 cm.

The Next Step in the Stellarator Programme

Having attained such impressive results in the stellarator research, physicists are enthusiastically preparing for the next step towards the creation of a fusion reactor. Once again, the attempts to create new-generation stellarators are being undertaken simultaneously in several countries.

A modular version is envisaged for the new-generation stellarator in the FRG. The stellarator will consist of identical parts (modules) and will have the shape of a pentagonal torus rather than a circular one. The coils will have an exotic undulatory shape. It is not a simple task to prepare such coils, but the problem is somewhat simplified by standardization: only four different types of coil are used. The stellarator being designed is very large with a major radius of 2 m, and a plasma radius of 0.22 m. It is planned to heat the plasma by radiowaves and neutral beams. Each of these methods will add a power of at least 10 MW to the plasma.

The construction of such a device will naturally take many years and will require an enormous investment. But it will be a very significant step towards the creation of a stellarator fusion reactor. Not only will it bring the plasma parameters close to fusion conditions, but will also provide experience in the construction and operation of stellarators with modular magnetic systems.

The new-generation stellarators in the Soviet Union use the helical windings as before. However, these windings are not deployed in the same manner as in a "classical" stellarator (the so-called torsatron version). The current in these units flows in the same direction in both conductors of the helical winding.

Such a helical winding produces a longitudinal field and a helical field simultaneously, and hence extra coils to produce the longitudinal field become unnecessary. True, a very strong vertical field is produced in this case, and a special compensating coil carrying a very strong current has to be used to eliminate this field.

The torsatron type of stellarator was proposed in 1968 by a group of French scientists led by C. Gourdon. The main advantage of this device is that the forces acting on the elements of the helical winding can be considerably reduced by a suitable choice of the lead of the winding, thus simplifying the design of the stellarator.

Two new-generation stellarators are being designed in the Soviet Union. These are the L-3 stellarator at the Lebedev Physical Institute of the USSR Academy of Sciences (Fig. 8.7) and the Uragan-3 stellarator.

The L-3 device will replace the existing L-2 unit. Its torsatron helical winding will consist of two copper busbars with a constant angle of winding relative to the torus axis. The value of this angle is chosen so that the magnetic surface confining the plasma occupies the largest possible fraction of the vacuum chamber. This is necessary in order to use the volume of the magnetic field effectively. The plasma in the L-3 will occupy 70% of the volume of the magnetic field. Thus, the stellarators can be compared with the best tokamaks even in this parameter.

The plasma size in the L-3 will not be especially large. The major radius will be 1.6 m, and the minor radius will be 0.25 m. This is even smaller than that in existing large tokamaks, not to speak of the ones to be constructed. But the lifetime and parameters of the plasma should be quite good even for such a small size owing to the excellent confining properties of the stellarator field.

The main task of the new Uragan-3 stellarator, which is to be built at Kharkov, is to verify another potential advantage of stellarators. It will explore the possibility

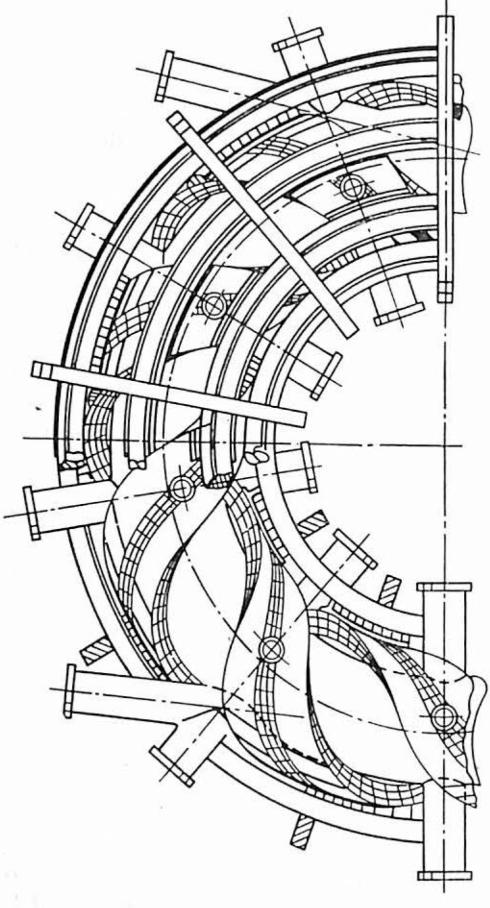


Fig. 8.7. Schematic diagram of the L-3 stellarator.

of using the helical field confining the plasma in the construction of divertors as well.

Figure 8.8 shows a sectional view of the Uragan-3 stellarator. It has a winding of

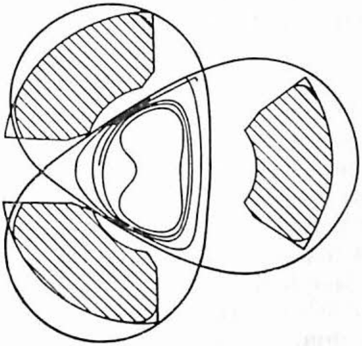


Fig. 8.8. Arrangement of the magnetic surfaces in a cross-section of the Uragan-3 stellarator.

torsatron type with three pairs of helical conductors. This means that there are only three helical busbars. The current flows in the same direction in all the three busbars. The magnetic field has a rather complex structure, and nearly triangular magnetic surfaces are formed in the central region. The plasma is confined within these surfaces. As the distance from the centre increases, the angles between the surfaces become more acute. Finally, a triangle is disconnected at the vertices, and magnetic

field lines no longer form closed magnetic surfaces but instead go round the busbars of the helical winding. A plasma particle hitting such a field line move far from the remaining plasma. The helical windings of a stellarator are normally arranged outside the vacuum chamber. For this reason, plasma particles leaving the plasma and entrained by such a field line strike the wall of the vacuum chamber and knock impurity atoms out of it. In order to prevent this, the vacuum chamber in the Uragan-3 is very large so that the busbars of the helical winding are enclosed in the vacuum. A receiver for the plasma particles is installed on the outer side of the helical busbars. It is a small channel with a narrow entrance and a very high vacuum. Plasma particles entering the receiver knock impurity atoms out of the walls, but it is very difficult for these atoms to find their way back to the plasma. Most of them return to the walls of the channel, but because they have a much less energy than plasma particles, they adhere to the wall without knocking out new particles. In order to enhance adhesion, the walls of the channel are continuously sprayed with titanium.

Physicists at Kharkov have come up with an elegant solution while designing the Uragan-3 stellarator. Three very large divertors are formed over the entire length of the unit. No additional windings are re-

quired. If such a divertor is found to be effective in reducing the impurity flow into the plasma, this will be yet another advantage of stellarators as reactors.

Experiments on the Uragan-3 stellarator have already begun. The basic aim of the experiments on the device is to determine the behaviour of impurities in such a system and the efficiency of divertor operation.

Administration Again

The success of stellarators posed a dilemma for the administration of the fusion research programme in the USA. As a result of the decisions taken in 1969 following the success of tokamak research in the USSR, about 20 tokamaks were built in the USA. However, no stellarator was constructed during this period and the administration had to rectify the situation.

It is symbolic that one of the first new-generation stellarators is being designed at the Plasma Physics Laboratory of the Princeton University. This project envisages the conversion of the trendsetting PLT tokamak into a stellarator, the same PLT that set up a record in ion heating (60 million degrees Kelvin). Other participants in the revived stellarator research programme in the USA include the Massachusetts Institute of Technology, the Uni-

versity of Wisconsin and the Oak Ridge National Laboratory. The basic design of these stellarators is the same as that of the Soviet and German stellarators, but their size is expected to be about 1.5-2 times larger. In the middle of 1983, the Oak Ridge National Laboratory received a grant of 15 million dollars to build a stellarator. This lent an air of reality to the revival of the stellarator research programme in the USA.

Chapter 9

Inertial Confinement

It was shown in the previous chapters that the many years of work on magnetic traps are about to bear fruit. In the best experiments, plasma confinement times of about 0.1 s have been attained. The day is not far distant when the confinement time required for the fulfilment of Lawson's criterion $n\tau > 2 \times 10^{20}$ s/m^3 will be attained. However, "not far distant" in a forecast for fusion research on the magnetic confinement means about 15-20 years. This is not surprising. Although the last 30 years have seen plasma confinement times in magnetic traps grew by a factor of about 10^4, every next step is more difficult. This can be compared with the reduction of the time required for a runner to cover 100 m in training. It does not take long to reduce his time from 20 to 15 s, but it is much more difficult to reduce it from 11 to 10 s. For this reason, the search for other approaches to nuclear fusion continues despite the advances in magnetic confinement.

Various lines of attack can be plotted in density-confinement time coordinates (Fig.

9.1). In these coordinates, the threshold to be overcome, viz. Lawson's criterion $n\tau > 2 \times 10^{20}$ s/m^2, is a straight line.

It can be seen that the controlled-fusion line can be approached in different ways. This is because it is only the product $n\tau$ that is important for a fusion reactor, while the values of n and τ can be chosen arbitrarily.

Some researchers have been looking at low-density plasmas which it was hoped would be easier to handle, but the confinement times for such plasmas have to be

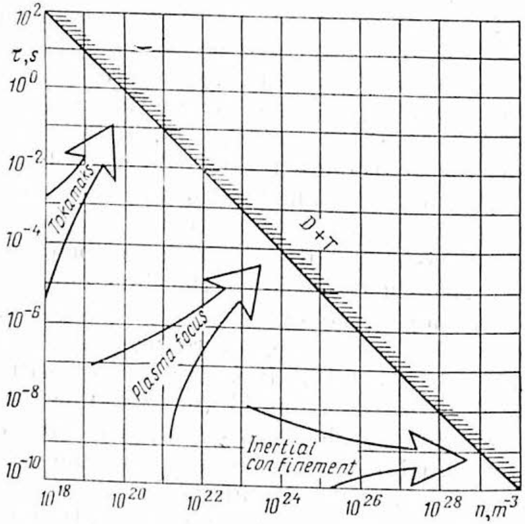


Fig. 9.1. Another battlefield map.

quite long. This approach was used in the best magnetic traps, viz. the tokamaks and stellarators. The plasma density n in these devices will be about 10^{20} m^{-3}. The pressure of such a plasma at fusion temperature will only be a few atmospheres, and it is not difficult to produce a magnetic field capable of confining it. However, the confinement time must be as long as a second. For the time being, the plasma seeps through the magnetic field and escapes from the trap within a twentieth of a second.

Other physicists are looking at very dense plasmas. A device known as the "plasma focus" was created at the Kurchatov Institute of Atomic Energy. The plasma density in the plasma focus is nearly 10^{24} m^{-3}. This means that it is sufficient to confine the plasma just for a tenth of a millisecond, but even this is not easy. For the time being, experimental plasma confinement times are still only tenths of this value.

It is possible to continue and use a plasma with a density of, say, 10^{29} m^{-3}. The confinement time for such a plasma would be just 10^{-9} s, but how would it be confined? The pressure of such a dense plasma at 100 million degrees Kelvin would exceed 10^9 atmospheres, and there is no way known to confine it. At any rate, the magnetic fields available at present are too weak,

Suppose the Plasma Is Not Confined at All?

This idea emerged even before that of the magnetic confinement. When the hydrogen bomb was created, it was found that at a high density and a temperature of 100 million degrees Kelvin, when the plasma pressure reaches million atmospheres and the plasma cannot be confined in any way, it dissipates rapidly, but not instantaneously. Inertial forces prevent the plasma from dissipating instantaneously and it takes about a few millionths of a second to overcome these forces. This is sufficiently long for the liberation of a huge amount of energy in the plasma. This method of plasma "confinement" (when actually there is nothing to confine it) become known as the inertial method.

In spite of the astonishing simplicity of this method, it was almost forgotten during the first years of the work on the fusion programme. As a matter of fact, there was no way of heating the plasma to fusion temperatures over the short period corresponding to inertial confinement. To be more precise, a method of this kind, viz. the explosion of a uranium charge, did exist, but it led to completely uncontrolled fusion.

Scientists recalled inertial confinement when the first lasers were designed. The remarkable property of the laser beam, viz. its ability to concentrate a huge power

in a small volume, immediately triggered the idea of employing a laser to heat small grains of matter to fusion temperatures. This would also lead to an explosion, but if the grain is small enough, the explosion will be small, and its energy can be used for peaceful purposes.

This idea emerged simultaneously in many countries at the beginning of the 1960s and up to 1972 it was developed secretly like magnetic confinement had been. In 1972, the veil of secrecy was removed and information was extensively exchanged at the International Conference on Plasma Physics and Controlled Nuclear Fusion Research in Moscow. It turned out that both Soviet and American scientists had arrived at the same ideas. The Americans were ahead in their computer simulations of plasma heating by lasers, while the Soviet physicists led in experimental studies.

At the time, a few devices were operating under the guidance of Academicians N.G. Basov and A.M. Prokhorov at the Lebedev Physical Institute of the USSR Academy of Sciences. For the first time, a plasma was being created and heated in these devices with laser beams.

First Estimates

At first, a laser fusion reactor seems very simple in design. A mixture of deuterium and tritium is frozen into a small ball and

a powerful laser beam is focussed on it, and that is all.

The density of solid hydrogen is about 4×10^{28} m^{-3}. This means that in order to obtain $n\tau \approx 10^{20}$ s/m^3, the confinement time τ should be approximately 2.5×10^{-9} s (2.5 billionth of a second, or 2.5 ns). If a grain of the mixture of solid deuterium and tritium is heated to 100 million degrees, it will explode at a velocity v of about 10^6 m/s. The explosion time depends on the grain size r: $\tau = r/v$. In order to obtain $\tau \simeq 2.5 \times 10^{-9}$ s, the grain radius should be about 2.5 mm, i.e. the grain should be of the size of a pea. The reactor turns out to be quite minute. True, a laser is also needed. We saw that the duration of the laser pulse should not be longer than 2.5 ns, but then what must the radiation energy be? It turns out that 12.3×10^6 J of energy is required to heat a 2.5-mm ball of a deuterium-tritium mixture to 100 million degrees Kelvin, Yes, well...

What to Do?

These calculations were first made in the early 1960s when lasers had just appeared. Even at that time a laser pulse lasted 20-30 ns and it was known how to make it shorter. But as for the energy... Laser pulses then had energies of a few joules.

Thus, before staging an experiment, ways

had to be found to reduce the energy required to heat the plasma to a reasonable level. Several ideas were put forward.

The enormous amounts of energy were theoretically obtained because deuterium-tritium target at which the laser must be aimed is very large. However, reducing its size would decrease the time needed for it to explode and Lawson's criterion $n\tau \simeq 10^{20}$ s/m^3 would be violated. But what would happen if the plasma density could be increased and what would happen if the pea is compressed just when the laser beam hits it?

How can it be compressed? Very simply and with the same laser. The whole pea cannot be heated at once. At first, the outer layer will be heated and vapourized. It will be converted into the plasma and dissipate. This gives rise to a recoil like in a jet engine. This force will press on the pea from the side of the laser. If several lasers are used to irradiate the pea from all sides, the reaction pressure will cause uniform compression and the matter density will be increased. Detailed calculations showed that the reaction forces cause a pressure of hundred million atmospheres and may indeed increase the matter density considerably. It turned out that if the density of the matter at the centre of the grain is increased by a factor of 100 as a result of compression, the required energy of the laser pulse drops to a million joules. And

if the compression ratio is 10 000, the energy is reduced to just 200 kJ.

True, what we require is not just 200 kJ over 2-3 ns, but an energy pulse accurately programmed in time whose power should increase with time according to a precisely calculated law.

If, however, a pressure of even several hundred million atmospheres is simply applied to a ball made of hydrogen isotopes it will not be compressed very much. A shock wave arising in the surface layer where the pressure is applied propagates to the centre and heats the substance before the compression wave reaches it. As a result of the heating, the pressure rises and prevents the fuel from being compressed to the required value.

In order to avoid this, shock waves should not be allowed to form. To do this, the laser power (and hence the pressure on the surface of the hydrogen grain) must be increased smoothly following a curve calculated beforehand. This curve is shown in Fig. 9.2. At the beginning, the laser power must be quite small, but by the end of the process it must be incredibly large with almost half the total energy being emitted during the last 0.1 ns. The first half of the energy is mainly spent on compressing the target, while the other half is spent to heat the plasma to the temperature needed to initiate the fusion reaction.

When the plasma is compressed to 1/10 000th of its previous volume, the mass density of the deuterium-tritium mixture at the centre of the target attains a record value of 1 kg/cm^3! No substance on Earth has such a density. At such a density,

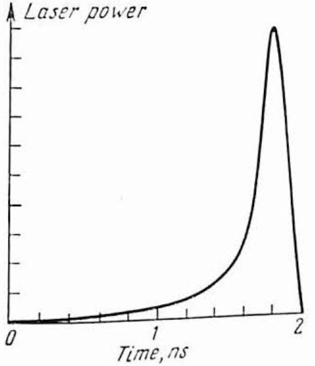


Fig. 9.2. Shape of the laser pulse for compressing a plasma without exciting shock waves.

the fusion reactions would not proceed as they do under normal conditions. The neutrons and alpha particles (^{4}He nuclei) that are generated do not leave the target during a fusion reaction at this density, and instead transfer a considerable fraction of their energy to other particles. The energy of the laser pulse is therefore only required to compress the target and

to provide the initial heating of the plasma up to the fusion temperature. Thereafter, the temperature is maintained by the energy of the fusion reactions. Hence, the liberated energy may be thousands of times more than the energy spent to initiate the reaction.

Naturally, this brilliant idea caused a burst of enthusiasm. The development of laser technology was so rapid that by the end of the 1960s, when these calculations had been completed, lasers with pulse energies of up to 100 J appeared. Thus, we take two thousand lasers and ...

Let Us First Try with Nine

Before constructing a giant device operating with two thousand lasers researchers naturally first had to verify experimentally the correctness of the ideas on which the calculations were based.

The maximum pressure which could be attained under laboratory conditions at that time was of the order of a few million atmospheres. The density of solids could only be increased several fold with this pressure. However, the pressure had to be raised many times and the compression ratio had to be elevated several thousandfold. The success of the experiment depended on the behaviour of solid hydrogen under such unusual conditions.

There were several other unknowns. During the compression process, a plasma heated to a few million degrees Kelvin appears on the outer surface of the grain. The success of the experiment also depended on the accuracy with which the behaviour of this plasma was taken into account in calculation, and plasma is known to be capricious. It was known from the magnetic confinement experiments that nobody had yet been able to predict its behaviour completely.

The most important question was whether the plasma would absorb the laser radiation.

The ordinary absorption mechanism, which is due to collisions between particles, becomes ineffective at high temperatures because the collision frequency rapidly decreases with increasing temperature. This means that if no new absorption mechanism appears, the plasma will become transparent to laser radiation long before the temperature reaches the required value. Fortunately, by that time physicists had accumulated a great deal of experience in handling the plasma, and its properties and behaviour were known to a certain extent. For instance, the absorption of electromagnetic wave energy by plasmas had been analyzed in detail in connection with the problem of plasma heating by radiofrequency electromagnetic waves.

It was found during these investigations that there are other absorption mechanisms

in the plasma in which particles move collectively in addition to classical absorption due to collisions in which each particle acts as an individual.

It has been known for a long time that collective motions of electrons do exist in plasmas. For example, it leads to the reflection of electromagnetic waves from plasmas. For each wavelength, there is a critical plasma density. If the plasma density exceeds this value, an electromagnetic wave cannot propagate in the plasma. A collective motion of electrons leads to the reflection of the electromagnetic wave from the plasma as from a good mirror. It is well known that light, including laser radiation, consists of electromagnetic waves. The critical plasma density for light with a wavelength of 1.06 μm, which is what is emitted by the most powerful (neodymium glass) lasers, is 10^{27} m^{-3}. The wavelength of a CO_2 laser is 10.6 μm, the critical plasma density being 10^{25} m^{-3}. Both these critical densities are much lower than the number density $n = 4 \times 10^{28}$ m^{-3} of atoms in solid hydrogen. After the first portion of hydrogen on the surface is heated, ionized, and converted into the plasma, the plasma density decreases from about this value to zero with increasing distance from the surface of the target. A region with a plasma density of 10^{25}, or even 10^{27} m^{-3} will emerge at a certain distance from the target surface.

A laser beam reaches this region on its way to the surface of the target, and is reflected due to the collective motion of electrons.

Very complicated processes occur in the neighbourhood of the critical plasma density. The collective motion of the electrons not only causes the reflection of the incident wave, it also excites particle oscillations in the plasma which propagate into the plasma in the form of plasma and acoustic waves. A plasma is a type of gas (even if it consists of charged particles), and acoustic waves exist in plasmas as in any other gas.

When a plasma interacts with a light wave emitted by a laser, all these complex processes occur in a small space whose size is comparable with the wavelength of the laser radiation, i.e. of the order of a micrometre. The experimental investigation of these processes is therefore very difficult.

The exact mechanism of the absorption of laser radiation and the processes accompanying it are still unclear. The laser radiation is absorbed in the region where the plasma density is close to the critical value rather than near the surface of the target. This creates another problem: the heat from the absorption region must reach the target surface.

The electron thermal conductivity plays a major role in the heat transfer process. The conductivity which is responsible for

the main difficulties in magnetic confinement experiments and favours the use of lasers in the controlled fusion problem. But how will the plasma behave in this case?

In order to obtain answers to all these questions at the least possible cost, a few small lasers were designed for the first experiments at the laboratories headed by Academicians N.G. Basov and A.M. Prokhorov at the Lebedev Physical Institute of the USSR Academy of Sciences. The most powerful of these lasers had nine channels, each channel being able to produce a pulse with an energy of about 100 J. This laser was called a Kalmar after the Russian name for the squid. For a few years, it was the most powerful laser in the world.

By using a system of mirrors, the nine laser beams from the Kalmar were directed to a vacuum chamber with a tiny target ball at the middle. All the nine beams were focussed with lenses on the target so as to illuminate it uniformly from all sides simultaneously.

In the first model experiments, the target was made of polythene in which hydrogen was replaced by deuterium. This was done in order to get rid of the complex hydrogen freezing technology. Tritium was not used at all in these first low-energy experiments since the aim was not to obtain any nuclear power. It was important to verify in principle whether or not the heating

and compression of the target will proceed as predicted. In the experiments, the deuterium was used for diagnostic purposes. If the temperature could be raised to a few million degrees Kelvin, a few fusion reactions would be observed and the number of neutrons generated in these reactions would yield a figure for the temperature obtained. Thus, the target was a deuterated polythene ball having a diameter of 0.2 mm.

Finally, the experiments were started. The plasma exhibited its adverse nature at once. The laser, which had been constructed and tuned after a great deal of effort, was spoiled by the very first shot. The light reflected from the plasma returned to the laser output and after going through all the stages in reverse order was amplified to such an extent that the instrument was damaged. The higher the output power of the laser and the better the beam is focussed, the larger the fraction of reflected light. A special shutter had to be invented for passing the light from the laser and cutting off the light reflected by the plasma. Fortunately, the fraction of reflected light only increases with increasing laser power up to a certain limit, after which it starts to decrease. Thus, this difficulty was overcome.

It was also difficult to attain a sufficiently uniform irradiation of the target from all sides. The power of all nine laser beams

and their focussing on the target surface had to be strictly identical, otherwise uniform bulk compression is not possible.

These and many other difficulties were ultimately overcome. In 1972, a 30-fold compression of the polythene target was obtained in some especially successful shots. The temperature at the centre of the target reached five million degrees Kelvin and a pressure of a few billion atmospheres was attained. Nuclear fusion reactions were initiated under these conditions, and the generation of neutrons was recorded.

Although the amount of neutrons was not very large (about a million neutrons per pulse), the correctness of the main ideas underlying laser nuclear fusion was confirmed. Thus, the construction of more powerful devices could now be planned.

Forward to the Attack!

Following the successful start on experiments on laser fusion, the scientists doing the research were infused with optimism.

The coincidence of the experimental results with the predictions of the theory allowed scientists to embark confidently upon the design of new units. Although it followed from the calculations that the setup would be complex and expensive, the expected results were enough to support the construction of the device. Indeed, controlled

fusion could be attempted using a laser with an output power of a few hundred kilojoules.

The proponents of the magnetic confinement approach were rather sceptical about the optimism of the laser enthusiasts. I.N. Golovin, one of the developers of the tokamak, formulated this attitude in the form of a theorem: "The fusion fortress is surrounded by a wall which is equally high all the way around. If it seems to advocates of the new approach that the wall is lower from their side or there is a breach in it, it simply means that this approach is young."

The construction of a giant laser with an energy of a few hundred kilojoules was postponed. Instead, it was decided to construct several devices which operate at an energy of 10 kJ for a more detailed investigation of the physical processes involved in plasma heating by laser beams.

By the end of the 1970s, new-generation lasers had been designed in many countries. A series of new devices were put into operation. These included the UMI-35, Mishen-2, and Delfin lasers in the USSR, and the Helios, Shiva and Nova lasers in the USA. Considerably smaller, but still impressive, devices were constructed in the FRG, the UK, and France.

At the same time, a detailed analysis of the processes occurring in a target under

laser irradiation was continued. The results of these investigations confirmed a well-known aphorism which had been formulated by plasma physicists, namely, that the product of optimism and the level of knowledge is a constant. As information about the interaction between plasmas and laser radiation was accumulated, the optimism of the supporters of laser fusion faded.

The Heat Transfer Rate Is Too Low!

The first obstacle to be encountered was that the measured electron thermal conductivity turned out to be considerably lower (by a factor of several dozen) than the expected value.

The reason for this low thermal conductivity was the magnetic fields that are spontaneously generated in a plasma irradiated by a laser beam. These fields are astonishingly strong (hundreds of teslas). It is very difficult to produce these fields deliberately. They can only be obtained for a millionth of a second and the coils generating them literally explode due to the forces emerging in the process. However, in a laser plasma these fields are spontaneously induced just where they are not needed! The small electron thermal conductivity reduces the evaporation rate from the surface of the target, and hence the value of the reaction force compressing it. Therefore, a

much more powerful laser had to be designed to obtain the required compression ratio.

But what is the origin of these spontaneous magnetic fields? A number of experiments were required and detailed measurements of the plasma density and temperature and their variations in the vicinity of the target had to be made. It was found that the reason lies in the insufficiently uniform distribution of laser radiation over the target surface. The plasma temperature is higher where the laser radiation is especially bright. The temperature difference causes difference in pressure, which in turn is responsible for an electron flow (in the same way as the nonuniform heating of the Earth's surface by sunlight generates wind). The electron "wind" is the same as an electric current. It is these electron currents that generate the magnetic fields. Once a cause is found, a way to eliminate it can be sought. The number of laser beams used to irradiate the target in a laser reactor should be increased, and the illumination will be more uniform.

The Heat Transfer Rate Is Too High!

As soon as physicists learnt how to control the magnetic fields in order to increase the heat transfer rate from the region of absorption of laser radiation to the surface of the target, it turned out that the rate

of heat transfer to the central regions of the target was too high! The target core was somehow being heated before it was being compressed. From the very outset this effect was expected as being due to shock waves, and special measures had been taken against them. It turned out, however, that the centre of the target was being heated in the absence of shock waves. The consequence is insufficient compression.

It was found that the trouble is associated with fast electrons generated where the laser radiation is absorbed due to the plasma instability.

The Light Pressure Is Three Million Atmospheres!

The plasma instability develops in the region where the laser radiation is absorbed only at a sufficiently high intensity of laser beam. In modern experiments, the laser's intensity at the target reaches the fantastic value of 10^{20} W/m^2.

With such an intensity, the light pressure reaches three million atmospheres! That's what the laser is! It is interesting to recall that about 75 years ago (at the beginning of this century) P.N. Lebedev had to use all his experimental skill to measure the pressure of light.

Under a light pressure of million atmospheres, the plasma starts to move. Figure

9.3 shows the decrease in plasma density with increasing distance from the target. At a distance of 3 μm from the target surface, the plasma density drops abruptly.

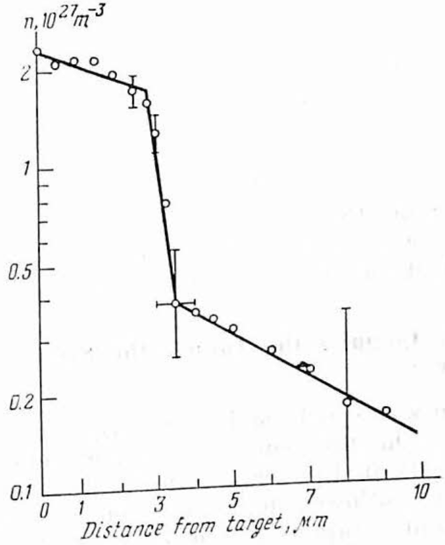


Fig. 9.3. Plasma density vs. distance from the target surface.

This is a result of the light pressure. In this region, where the light pressure becomes equal to the pressure in the plasma, some intense processes occur. The detailed mechanism of these processes is not known and they are still being investigated. Enor-

mous electric fields emerge during these processes and these electric fields accelerate electrons in the plasma. The fast electrons arrive at the cold core of the target, heat it, and thus prevent it from being effectively compressed.

The complications introduced by spontaneous magnetic fields and fast electrons necessitated a reestimation of the energy of the laser pulse needed to initiate a fusion reaction. The estimates jumped by an order of magnitude and became a million joules again, thus making the fusion dubious. New ways to reduce the required energy had to be found immediately.

The More Complex the Target, the Simpler the Laser

The main way was to make the target more complex. The first successful experiments with targets in the form of uniform solid balls were followed by experiments with more complex targets in the form of glass spheres 100-200 μm in radius and a wall thickness of 2-3 μm. Strange as it may seem, such a sphere can be filled with deuterium under a pressure of a few dozens of atmospheres which the sphere withstands (Fig. 9.4*a*).

To the surprise of the physicists, this was not very difficult technologically. Within two years the technology for manu-

facturing such spheres for laser targets was developed in many countries, including the USSR and the USA. It was not very complicated or expensive, although there were stringent requirements on the targets.

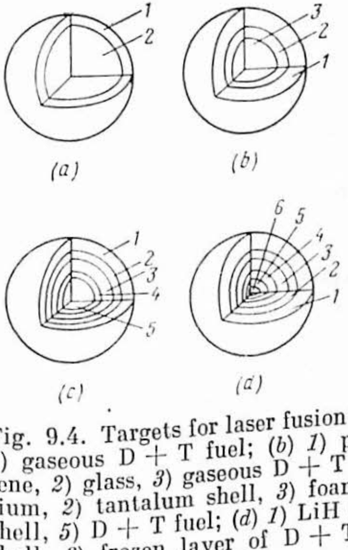


Fig. 9.4. Targets for laser fusion: (*a*) *1*) glass shell, *2*) gaseous D + T fuel; (*b*) *1*) polytetrafluorethylene, *2*) glass, *3*) gaseous D + T fuel; (*c*) *1*) beryllium, *2*) tantalum shell, *3*) foam plastic, *4*) gold shell, *5*) D + T fuel; (*d*) *1*) LiH shell, *2*) tantalum shell, *3*) frozen layer of D + T fuel, *4*) cavity, *5*) gold, *6*) D + T fuel.

Glass components are mixed with water, and the mixture is sprayed from a height of 1-2 m in a vertical furnace. As the drops fly through a region at a temperature of about 1000°C, the glass components fuse,

and the glass is formed. The water evaporates in the process and the steam blows small spheres of glass. The diameters of the spheres range from 20 to 800 μm, with wall thicknesses of a few micrometres. What is more important, the surface irregularities amount to only hundredths of a micrometre. It remains only to select spheres of the required diameter. About 10% of the glass is converted into such spheres.

But how can they be filled with nuclear fuel? That too was not very difficult. The glass spheres are heated in an atmosphere of the deuterium-tritium mixture at an appropriate pressure. At high temperatures, the hydrogen isotopes diffuse easily through the thin glass shell and fill the interior of the sphere. After cooling, the diffusion rate through the glass sharply drops, and the gas cannot escape from the sphere.

If necessary, the hydrogen within a glass sphere can be frozen. Moreover, by successively freezing and thawing, the deuterium-tritium mixture can be made to freeze in a uniform layer 2-3 μm thick on the inner surface of the sphere.

A large number of experiments with glass-sphere targets were carried out with laser pulse energies of a few hundred joules and a pulse duration of 0.1 ns. The number of neutrons recorded in these experiments attained values of 10^{10} and the $n\tau$ product reached 10^{18} s/m^3.

The targets can be improved by increasing the shell thickness without increasing its mass. Then the reaction force emerging during the evaporation of the light outer shell would compress the inner glass shell and the deuterium-tritium gas. If the outer shell is so thick that the glass remains unevaporated till the end of the laser pulse, it will protect the deuterium-tritium gas from fast electrons and X-rays. In order to eliminate shock waves, the laser pulse has to be carefully controlled in time. The large thickness of the shell makes it possible to increase the duration of the laser pulse and hence simplify the problem. The outer shell was made of a very light material, such as polytetrafluorethylene, polythene or beryllium. Such a target was designed for the compression mode which has become known as the cold piston. Unlike previous targets, the glass shell must remain comparatively cold all the time. It is used as a piston to compress the gas (Fig. 9.4*b*).

Experiments with these targets ensured considerable progress in terms of both the compression ratio and the temperature. The deuterium-tritium mixture was compressed to a density 50 times higher than that of liquid hydrogen. At the moment of maximum compression, the temperature attained the cherished goal of 100 million degrees Kelvin, the $n\tau$ product being 2 $\times$

10^{18} s/m^3. The energy liberated in the fusion reactions now constituted 1% of the input energy.

An image obtained during an experiment of this type in the cold piston mode is shown in Fig. 9.5. The thin lines represent the cross-section of the initial spherical

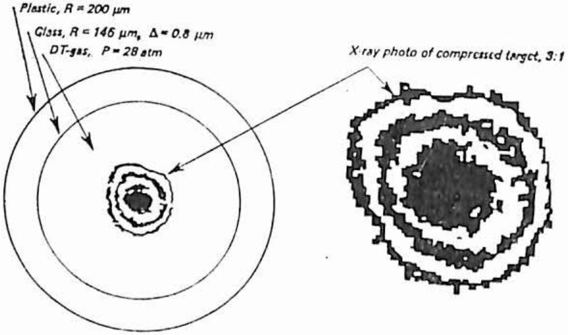


Fig. 9.5. Compression of the target by a laser pulse in a cold piston experiment.

target. It was a glass sphere with a radius of 146 μm and a wall thickness of 0.8 μm. The sphere was enclosed in a polymer shell so that its diameter was brought up to 200 μm and filled with a deuterium-tritium mixture at a pressure of 28 atm. The X-ray photograph of the centre of the sphere was obtained at the moment of the maximum compression of the target. A small hole in a lead screen served as the objective. The X-rays passing through this hole form

the image of their source on the film. This is similar to the technique used in visible-light photography many years ago.

The same image is shown magnified on the right-hand side of the figure. It can be seen that the compression in this experiment was quite symmetric and the volume occupied by the deuterium-tritium gas was reduced to 1/250th of its initial value.

In order to obtain such symmetric compression, the surface of the target must not differ from being an ideal sphere by more than 0.3 μm at any point. The modern technology of manufacturing targets can meet these requirements. Scientists were inspired by these technological achievements and designed even more complicated targets.

In order to obtain even better compression, the next-generation targets will contain many layers. The sphere consists of a thick outer beryllium coating, inside which there is a polymer layer with embedded tantalum grains, inside which there is a space filled by a porous foam plastic or by a gas under a low pressure. Finally the innermost shell is made of gold (Fig. 9.4*c*).

This construction envisages everything that can be imagined given our modern understanding of the processes occurring in a target irradiated by a laser beam. The two outer shells operate in the cold piston mode and produce a high compressing pressure. The layer of porous foam plastic

or gas is intended to protect the fuel from fast electrons. The inner gold shell protects the fuel from X-ray heating. The mass of the outer shells is considerably larger than the mass of the inner gold shell, and this almost doubles the compression rate of the deuterium-tritium mixture.

Experiments with such targets are at present being planned. Detailed calculations have been made and they show that with a laser pulse of energy 15 kJ, the deuterium-tritium mixture in such a target can be compressed to a density exceeding 500-1000 times the density of liquid hydrogen. The energy liberated in fusion reactions will then constitute 0.1 of the supplied energy. For a laser pulse energy of 200 kJ, a tenfold gain in energy will be attained. However, for an economically viable energy production, this is too small. Taking into account the rather low efficiency of the laser, a gain factor of about 1000 is required for economic operation of the reactor.

The target should therefore be made even more complicated. In all the previous targets, two problems were solved simultaneously: the compression of the fuel and its heating to the fusion temperature. In order to save energy, these processes should be separated. After all, what we need is just to trigger the reaction. In a sufficiently compressed fuel, the fusion will proceed spontaneously. Therefore, all the fuel should

be compressed, but only some of it should be heated to fusion temperature. This can be achieved with a target whose structure is shown in Fig. 9.*4d*.

Generally, it resembles the previous target: it contains layers of beryllium, a polymer with tantalum, gas, and gold, but the fuel is separated into two parts. The larger part is contained in a layer frozen onto the inner surface of the second layer, while the smaller part is placed, as before, within the innermost gold shell. Most of the fuel in the target is subjected to cold compression, and only the fuel contained in the gold shell is heated to the fusion temperature.

Calculations show that an energy gain factor of 1000 can be obtained in such a target using a laser pulse with an energy of a million joules (1 MJ). Thus, this system can operate as a reactor.

Lasers for Controlled Fusion

The target, even if it is very complex, is still not everything, not even half the job. The main complications and expense of a nuclear fusion reactor are associated with the construction of the laser. The requirements on a laser for controlled fusion were gradually formulated during the investigation, and the main features of such a laser can be outlined even now: in spite

of all the improvements in the targets, the laser output energy must still range from 1 to 10 MJ, the pulse duration should be 5-10 ns, the radiation wavelength must be 0.2-0.6 μm, the pulse repetition frequency is expected to be 1-10 pulses per second, and the efficiency must be 10%.

For the sake of comparison, we present the two best modern laser systems, viz. a neodymium glass laser having an output energy up to 20 kJ, a pulse duration of 1-2 ns, a wavelength of 1.06 μm, a pulse repetition frequency of 1 pulse per hour, and an efficiency of 0.1%, and a CO_2 laser with an output energy of 10 kJ, a pulse duration of 1 ns, a radiation wavelength of 10.6 μm, a pulse repetition frequency of 1 pulse in 20 minutes, and an efficiency of 2-5%.

A comparison of these parameters shows that neither laser is fit for a fusion reactor. Some of these parameters will be considerably improved in future developments and brought to the required level. For the neodymium laser, these are the output energy, pulse duration, and wavelength. For the CO_2 laser, these parameters are the output energy, pulse duration, and efficiency.

However, some of parameters of the two lasers obviously cannot be improved to make them useable for a fusion reactor. For the neodymium laser, these parameters are the pulse repetition frequency and effi-

ciency, while for the CO_2 laser, it is the radiation wavelength. Therefore, new lasers must be created for the reactor. Research is underway in this direction, and the first candidates are lasers based on oxygen, sulphur, and selenium. These lasers will generate radiation with wavelengths of a few hundred nanometres and good efficiencies of the order of tens of percent. However, these lasers are at the initial stage of development and most effort is being concentrated on the improvement of existing laser systems.

The most powerful modern neodymium lasers are huge devices occupying spaces equivalent to whole apartment blocks. Every channel is a complex system of many dozens of components, and there may be tens or even hundreds of channels. For example, the Soviet Delfin laser has 12 channels with 18 output channels operating in parallel in each channel, or a total of 216 beams. There are 20 channels in the American Shiva laser, and this number will be increased to 50 in the improved Shiva-Nova version. As a matter of fact, the optical system of a laser is like the tip of an iceberg. Most of it, viz. the energy supply and cooling systems, is hidden under the surface (in the case of a laser, in the basement). For a CO_2 laser, the basement also contains the gas-provision apparatus. For example, the energy supply system of the Shiva-Nova laser includes a capacitor bank of 50 000 ca-

pacitors each rated at 20 kV. This bank of capacitors stores 250 MJ of energy which feeds 17 000 tubes to pump the laser.

It should be noted that because of the low efficiency of lasers, the electric supply systems of modern lasers are much larger than those of the largest tokamaks in terms of energy and power. For this reason, improving laser efficiency is very important.

Another extremely complicated task is to tune and adjust the optical system of a laser. A very accurately tuned optical cavity (resonator) is essential for lasing. A laser can only be accurately operated in the required mode with good tuning. As long as a single laser is concerned, there is no problem. However, when dozens of channels, each consisting of dozens of elements, have to be tuned simultaneously, thousands of components have to be matched, and quantity is transformed into quality. Lasing becomes practically impossible by manual adjustment. By the time a technician has reached the last stages, the first stages will have become detuned for some reason.

The problem can only be solved by automatic tuning. Indeed, the largest modern lasers operate with an automatic tuning system controlled by a high-speed computer.

Laser Reactor

Let us suppose that all the problems concerning the laser, target, compression, and initiation of the reaction have been solved. What will a laser fusion reactor look like and how will it operate?

The main feature of an inertial confinement reactor is its pulsed operation. It is clear from what we have said above that the laser pulse required to initiate the reaction must have an energy of about a million joules. Taking into account the laser's efficiency and the efficiency of converting thermal energy into electric energy, the energy gain factor required for positive energy output should be about 1000. This means that 1000 MJ of energy will be liberated in the target after each laser shot. This would be a considerable explosion. An explosion of 1 kg of TNT results in the liberation of 4 MJ of energy. Consequently, the TNT equivalent of such a nuclear explosion is 250 kg. This is a good-sized demolition bomb and such a bomb would have to be exploded in the reactor chamber at least every second.

Naturally, designers must think about how to make the chamber strong enough to withstand the explosion of such a bomb. Obviously, the chamber must be a large steel sphere with all the air pumped out of it. The target with all its shells has a mass of

about 0.01 g. This means that the huge energy liberated during each explosion is contained in a negligibly small amount of matter. The reactor walls must be strong

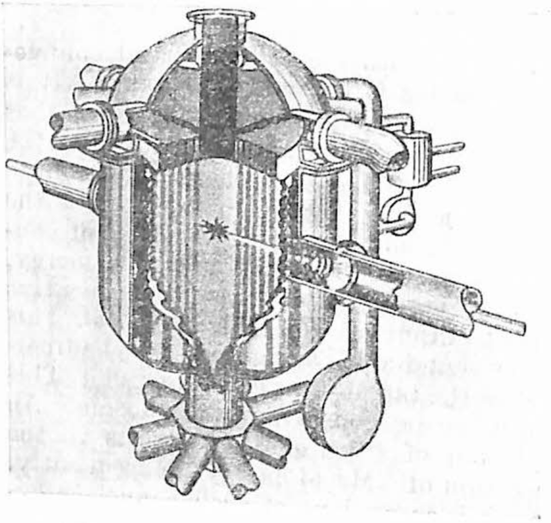


Fig. 9.6. The projected laser fusion reactor.

enough to withstand bombardment by alpha particles, neutrons, and the fragments of the target.

A diagram of one such reactor is shown in Fig. 9.6. The target is dropped into the chamber from the top and falls freely until it reaches the centre of the chamber. There

it is hit by laser beams. The liberated energy is absorbed by the first wall and converted into heat which is transferred through a heat exchanger to a steam boiler and then transformed into electric energy as at an ordinary electric power plant.

This reactor is designed for less stringent operation conditions than those discussed earlier. It is assumed for the design that only 100 MJ of energy will be liberated in the target (the TNT equivalent is 25 kg), but that this will occur 10 times per second. This is possible if an appropriate laser can be designed.

Other Methods

A laser with an output energy exceeding a million joules, with the required wavelength, pulse duration, efficiency, and pulse repetition frequency will in all probability be created, although it will be extremely expensive. Therefore, it is natural to seek other methods for plasma heating with the inertial confinement.

In recent years, hopes have been raised by the rapid progress in charged particle accelerators.

Acceleratorsappeared with the development of nuclear physics. Users wanted accelerators with ever larger particle energies. And this was done. The particle energy in a modern accelerator attains values of

tens and hundreds of billion electronvolts. However, the number of particles accelerated in such accelerators is rather small.

About ten years back, accelerators with relatively low energies (about a million electronvolts) but with huge currents of the order of 10^4 amperes appeared. They immediately began to compete with lasers in beam power. Their main advantages were simplicity and low cost. They consist of a high-voltage electric energy accumulator and a diode, viz. two metal electrodes in a vacuum tube. When a voltage of a million volts is suddenly applied to them, an electric current emerges spontaneously since the strong electric field tears electrons out of the metal and forms a beam of electrons which are accelerated to an energy of a million electronvolts. These electrons fly at a velocity very close to the speed of light. The effects predicted by Einstein's theory of relativity no longer have the form of small corrections, instead they determine the very nature of motion. For example, the electron mass is three times larger than the rest mass.

These electron beams obey relativistic laws and for this reason they are called relativistic beams.

Relativistic electron beams can be used to heat a substance to the fusion temperature with inertial confinement at least as well as laser beams. Unlike laser radiation, the

electrons are not caught by the plasma formed at the surface of the target and so they arrive at the target. Hence some of the problems facing the laser fusion do not exist for electron beams. However, the deep penetration of the electrons hampers the compression of the target, and hence the energy an electron beam must have to initiate fusion turns out to be considerably higher (10-20 MJ) than what is needed when a laser pulse is used. However, an electron beam with an energy of millions of joules is easier to obtain than an equivalent laser beam.

Electron beams are being planned in experiments on the Angara-5 device, which is nearing completion.

The Angara-5 is a giant device (Fig. 9.7). When completed, it will consist of 48 modules. Each module is an accelerator producing an electron beam with an energy of 2 MeV and a current of 0.8 MA. The pulse duration of the beam is 90 ns, and the energy carried by the pulse is 100 kJ. Thus, 48 modules can supply about 5 MJ of energy to a target in 30 ns. The compression ratio that can be expected with such an energy and the temperature developed in the target will be sufficient to initiate a fusion reaction.

The structure of the target needed to obtain fusion energy using relativistic electron beams is similar to that of the target

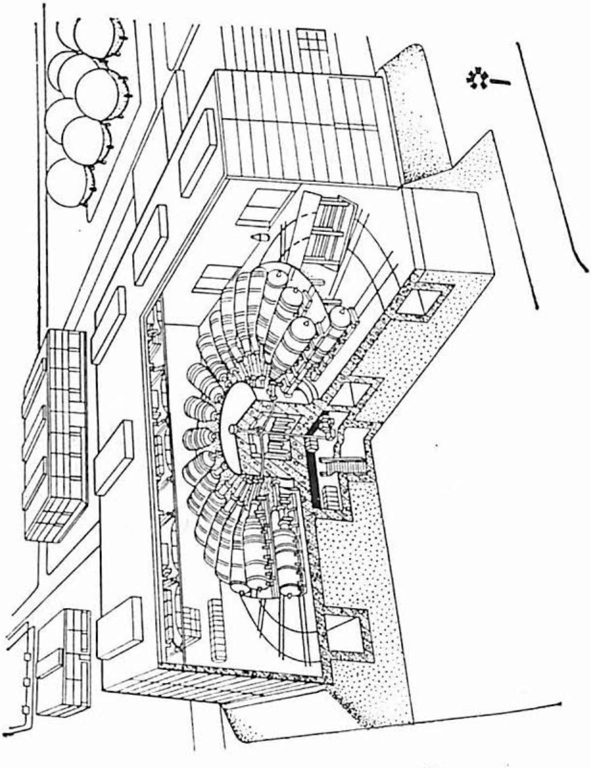


Fig. 9.7. The projected Angara-5 device.

for laser nuclear fusion. There is a slight difference due to the higher penetrability of the fast electrons as compared to laser radiation. For this reason, the outer shells of the electron beam targets are made thicker and heavy metals such as gold or tungsten are used.

The energy supplied to a reactor involving relativistic electron beams is normally estimated at 10-30 MJ. The efficiency of conversion of electric energy into the energy of an electron beam in modern accelerators is about 0.4. However, the efficacy of utilization of this energy to heat the target is rather low (about 0.1) due to large losses. Given the efficiency of the conversion of thermal energy into electric energy, it follows that a very large energy gain (of the order of 100 or 1000) in the target is required for a positive energy balance which is similar to what is needed in a laser reactor. Such an energy gain can be obtained by using a complex target in which the beam energy is utilized to ignite a small fraction of the thermonuclear fuel. Most of the fuel will then be taken to fusion temperatures by the energy liberated by the fusion reaction of the triggered fuel.

Thus, about 10^7 J of energy will be supplied to the target to operate a fusion reactor based on electron beams, the liberated energy being 10^9-10^{10} J. This corresponds to a powerful explosion (the TNT equiva-

lent of 10^{10} J is 2.5 tons). Calculations indicate that a steel sphere with a diameter of 20-30 m and a mass of about 1000 tons could withstand such an explosion. The explosions could be repeated every 10 seconds, so the thermal power of such a reactor would be about 10^9 W.

Using beams of heavy ions should simplify the situation. Having changed the polarity of the same accelerators, it is possible to accelerate ions of oxygen, argon or still heavier elements instead of electrons. The mean free path of such ions in a substance is considerably shorter than that of electrons. Therefore, the beams of heavy ions will compress the target more, and hence less energy will be needed to initiate the reaction. The energy liberated during the explosion of the target is reduced accordingly. However, the experiments involving the utilization of accelerated ions for controlled nuclear fusion are still at an early stage.

Another Look at the Battlefield Map

The development of the laser approach has been very rapid. In less than 12 years, laser fusion has traversed a path it took the classical approach of magnetic confinement 30 years to traverse.

Thus, despite the complexity of the problems still awaiting solution, laser research is being continued,

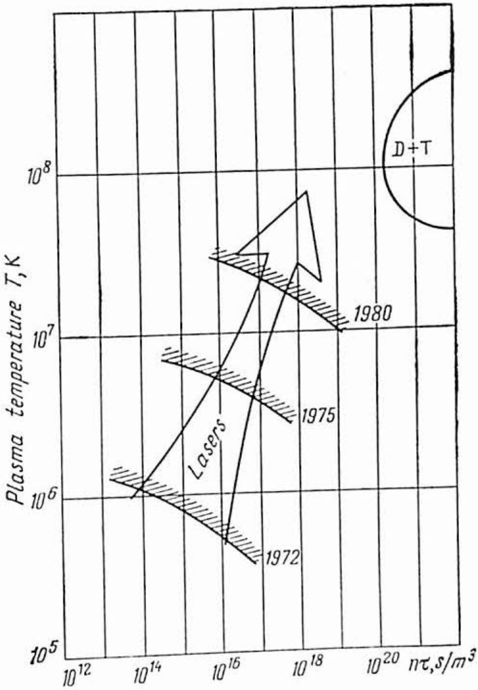


Fig. 9.8. The attack of the lasers is shown on the battlefield map.

Chapter 10

Muon Catalysis

An elegant idea emerged at the very outset of work on controlled fusion. It seemed that by implementing this idea, high temperatures would become unnecessary.

The high temperatures are required in nuclear fusion to get the deuterium and tritium nuclei within a distance of about 10^{-14} m of each other in spite of electrostatic repulsion. The repulsion arises because both nuclei have positive charges. If it were possible somehow to get rid of the charge, the high temperatures would become unnecessary.

This is achieved in fission reactions. The fission of a uranium nucleus in a reactor involves the absorption of a neutron. A neutron has no electric charge and so it can get as close to a nucleus as desired. Slow neutrons turn out to be even more effective than fast neutrons since the capture of neutrons, which results in the fission of the nucleus, is more probable for slow neutrons than for fast ones.

Nobody knows yet how to get rid of the nuclear charge, but the charge can be com-

pensated. This is done by arranging a negatively charged particle near the positively charged nucleus, and the system as a whole will become neutral. A well-known example is the hydrogen atom. The positive charge of its nucleus is compensated by the negative charge of the electron.

Unfortunately, this system cannot be used for our purposes. The electron in a hydrogen atom is 5×10^{-11} m away from the nucleus, while the minimum separation between nuclei during a collision of such two neutral systems is about 10^{-10} m, which is thousands of times larger than the range of nuclear forces. Therefore, no fusion reaction would occur during a collision between deuterium and tritium atoms.

If only the size of the atom could somehow be reduced to make it comparable with the range of nuclear forces, fusion reactions would be initiated by the collision of two atoms at a low temperature.

Strange as it may be, such an atom can be created! A negatively charged muon (mu-meson) can be used instead of an electron.

Muons are unstable particles which are created during nuclear reactions. The mass of a muon lies between the mass of an electron and that of a proton. The mass of a muon is equal to 207 electron masses. A negatively charged muon and a positively charged nucleus may form an atom known as a mesic atom.

According to the laws of atomic physics, the radius of an atom is inversely proportional to the mass of the lightest of the particles constituting it. Therefore, the radius of a mesic atom is about 1/200th of the radius of a hydrogen atom. At the same time, a mesic atom is electrically neutral like an ordinary atom. This means that two such mesic atoms may come within a distance of about 10^{-13} m, which is comparable to the range of nuclear forces. That's it! By using mesic atoms, nuclear fusion reactions can occur without any high temperature!

Indeed, this is really so. Moreover, historically things occurred the other way around: at first fusion reactions stimulated by muons were observed experimentally, and only then was the mechanism of the phenomenon explained and the idea of using the reactions for controlled fusion was put forth.

The story is as follows. Some strange events were observed in one of the first experimental investigations of muons. The emergence of a new muon with an energy of 5.4 MeV was observed in a liquid hydrogen bubble chamber after a muon had been decelerated and brought to a halt.

This is the energy liberated in the nuclear fusion reaction $p + D \rightarrow {}^3He$. The mechanism followed by this reaction turned out to be as follows: a muon (μ) comes to a halt

near the nucleus of a hydrogen nucleus, viz. the proton (p), and forms a mesic atom with it (μp). Then the mesic atom meets a deuterium atom (D) which is always present in liquid hydrogen as an impurity. As a result, the mesic molecule $p\mu D$ is formed. The negatively charged muon arranges itself between the positively charged hydrogen and deuterium nuclei and brings them together to a distance of about 10^{-13} m, and then the reaction of fusion of the ^3He nucleus takes place. During the reactions, the muon is liberated and can trigger other reactions. Thus, the muon acts as a catalyst since it triggers reactions without being consumed by it.

The beautiful idea of employing muon catalysis in a reactor based on nuclear fusion reactions emerged. Such a reactor would have considerable advantages over an ordinary fusion reactor since it would require neither enormous temperatures of ten million degrees Kelvin nor magnetic fields, and plasma would not have to be tamed.

As soon as the idea was put forth, scientists enthusiastically embarked upon its verification. The main difficulty in its realization is that the muon is not a stable particle. After two millionths of a second, a newly-born muon decays into an electron and two neutrinos. Therefore, the feasibility of a muon reactor depends on the

number of reactions the particle can catalyze during its such a short lifetime.

At the beginning of the 1960s, the rate of formation of the DμD mesic molecules was measured in a bubble chamber filled with liquid deuterium. It turned out that 1/6th of a D + D fusion reaction occurs on average during the lifetime of a muon. This means that only one out of six muons has enough time to catalyze a reaction, while the rest decay without doing anything. Is this enough? After all, a huge amount of energy, namely, 4 MeV, is liberated as a result of a single reaction. This energy should be compared with the energy spent on producing the six muons.

The minimum energy required to create any particle in a nuclear reaction can be calculated from Einstein's famous relation $E = mc^2$, which relates the energy to the mass of the particle and the speed of light. According to this relation, 0.5 MeV of energy is required to produce an electron. The mass of a muon is 207 times larger and so about 100 MeV are required to create a muon. This is the theoretical minimum energy. The energy needed in practice to create a muon is naturally a few times higher. Thus, even with theoretical estimates having spent about 600 MeV of energy to create six muons, we shall get a single nuclear fusion reaction which liberates 4 MeV of energy.

The situation, indeed, is hopeless.

This result ruled muon catalysis out from the list of promising approaches to controlled fusion. Most of the effort to get controlled fusion concentrated on magnetic confinement and heating to a temperature of ten million degrees Kelvin. Thus, this remarkable idea perished at the beginning of the 1960s.

Persistence of Singles or the Role of Academic Science

The muon catalyzed reactions continued to attract the attention only of a few researchers in various countries.

Theorists discovered that muon catalyzed nuclear reactions proceed in three stages. First, a complex of an ordinary deuterium atom D and a mesic atom μD is formed, and then the $D\mu D$ mesic molecule appears, which consists of two deuterium nuclei, a muon and an electron. This is followed by the nuclei coming together and then by the fusion reaction. The rate of the entire process is determined by the formation of the $D\mu D$ mesic molecule. As soon as the mesic molecule is formed, the fusion reaction will occur.

Experimentalists therefore began to study the process of formation of mesic molecules. A. Ashmore in the UK and J. Doedde in the USA carried out experiments in which

they measured the probability of formation of mesic molecules from deuterium and hydrogen nuclei. The results were in good agreement with the predictions of theory. The experimental results were gradually accumulated, and the accuracy of the theoretical calculations was improved. In fact, everything proceeded as it should be in the calm and sedate manner characteristic of academic science. Suddenly, a strange thing happened: the result of an elaborate experiment was found to deviate from theory.

In 1966, an experiment on the formation of mesic molecules in deuterium was staged under the guidance of V.P. Dzhelepov at the Joint Institute for Nuclear Research in Dubna. In this experiment, a diffusion chamber operating at room temperature was used to record nuclear reactions instead of the liquid hydrogen bubble chamber that had been used before. The results were quite unexpected: the nuclear fusion reaction occurred 10 times more frequently than in experiments with the bubble chamber.

What was wrong? It seemed at first that there was an error in the methodical part of the experiment. Checks showed, however, that there was no error. The Dubna experiment, like those made by Ashmore and Doedde, was carried out very carefully. A doubt arose which at first seemed quite improbable: perhaps, the prob-

lem was that the experiments had been staged at different temperatures.

In order to eliminate any shadow of doubt, a direct experiment was carried out in 1977 in Dubna: a vessel whose temperature varied between −200 and +100°C

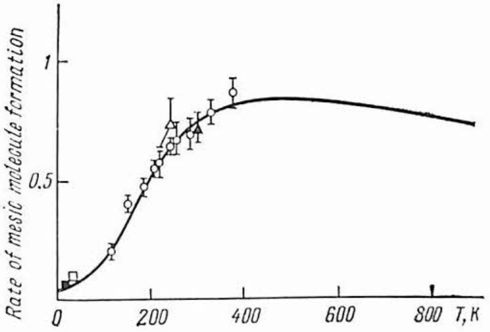


Fig. 10.1. Temperature dependence of the rate of formation of mesic molecules DμD. The symbols show the results of different experiments. The solid line corresponds to the predicted values.

containing gaseous deuterium was irradiated by muons. Sure enough, the probability of the formation of deuterium mesic molecules, and hence the yield of nuclear reactions, smoothly increased with temperature, and at 100°C they were about 10 times the values recorded at −200°C (Fig. 10.1).

Does it mean that temperature is the only important factor?

It's Impossible!

The nuclear physicists were understandably sceptical. There is a peculiar energy scale in nuclear physics. Reaction thresholds, as well as the excitation levels of nuclei, have values of millions of electronvolts. The temperature equivalent to these energies amounts to billions of degrees Kelvin. The energies that may affect these processes must be comparable to these values.

At the dawn of atomic physics, when the first nuclear process (radioactive decay) was discovered, scientists tried more than once to alter the rate of radioactive decay changing external conditions: they heated radioactive salts to thousands of degrees Kelvin, placed them in strong electric and magnetic fields, and so on. We now see that these attempts were naive since the external effects they tried are negligibly weak in comparison to the nuclear energy scale. Hence the idea that a temperature difference of 200-300 degrees could somehow affect the rate of a nuclear reaction was not met with enthusiasm, to put it mildly. However, the Soviet physicist E.A. Vesman proved as far back as 1967 that the nuclear process might be sensitive to temperature if the mesic molecule had a resonance level with a surprisingly low energy compatible with the thermal energy of the molecules at the temperature of the Dubna experiment.

Such Things Also Happen ...

I think there is no need to explain to the modern reader what resonance is. Examples with swings and the bridge that gave way under marching troops have been used far too often. The only thing important to note is that during resonance, the probability of the formation of a mesic molecules increases many thousand times.

However, to attain a resonance, there have to be several coincidences: the vibrational frequency of the complex comprising an ordinary D_2 molecule and a mesic atom μD must coincide with the vibrational frequency of the $D\mu D$ molecule formed by them. On the other hand, the energy of all these vibrations must be low enough. In order to discover whether there is a resonance level at such a low energy, a group of theorists from Dubna led by L.I. Ponomarev did the calculations for the formation of deuterium mesic molecules accurately.

In the earlier rough estimates, deuterium mesic molecules were found to have vibrational levels with energy corresponding to a temperature of a few million degrees Kelvin. A temperature of one hundred degrees was obviously insufficient to excite these levels, and no resonance increase in the reaction probability could be obtained as a result. A level with an energy equal to 1/1000th of this value had to be found. To do so,

the accuracy of the calculations had to be increased by a factor of one thousand. It is not common for the accuracy of such calculations to be attained in quantum mechanics.

This complicated task was brilliantly completed by scientists at Dubna. They managed to prove that a resonance level with all necessary requirements does actually exist in the mesic molecules DμD and DμT! The calculation of the rate of formation of deuterium mesic molecules DμD taking into account this level resulted in a temperature dependence which was in excellent agreement with the experiment. Moreover, for the deuterium-tritium mesic molecule (DμT), a fantastic result was obtained: a muon can form about 100 DμT molecules during its lifetime in the D + T mixture, and hence may cause 100 fusion reactions!

This calculation radically changed attitudes towards muon catalysis of nuclear fusion. Indeed, about 2000 MeV of energy will be liberated in a hundred D + T reactions, while only about 100 MeV must be spent to create the muon itself. Therefore, muon catalysis again becomes a promising method of attaining controlled nuclear fusion.

The new view naturally attracted the attention of experimentalists. A group of Soviet scientists at the Joint Institute for

Nuclear Research in Dubna immediately performed an experiment to measure the rate of the muon catalysis of a D + T reaction. A beam of muons from the Dubna synchrocyclotron was used in the experiment. The energy of the muons was 130 MeV. The target was a gaseous deuterium-tritium mixture. The D + T fusion reactions catalyzed by muons were recorded by using the delayed coincidence method. Before entering the target, the muon caused a flash in a plastic scintillator. This flash was registered by a photomultiplier. The creation of a neutron having an energy of 14.1 MeV was then registered by a neutron counter. Finally, fast-electron counters recorded the creation of the fast electron which results from the decay of a muon. Only if all these events occurred in the required sequence would a computer report the muon catalysis of a D + T fusion reaction. The scheme excluded the possibility of errors in the calculation of the number of reactions. If a muon is captured by another nucleus (for example, during its flight through the metal chamber's walls), a neutron is created, but no electron appears. On the other hand, the simple decay of a muon yields an electron, but the neutron will be absent. In both cases, the count is considered false and is not reported.

Meticulous measurements confirmed the predictions of the theory. The rate of

formation of DμT mesic molecules (and, accordingly, the rate of catalysis of the fusion reactions) is more than 100 times higher than the rate of decay of the muon.

Pocket Reactor

Muon catalysis has a number of advantages over "classical nuclear fusion" since neither the million-degree temperatures nor intricate magnetic fields are required. But that is not all. A muon reactor is just a gas-filled vessel (containing a deuterium-tritium mixture) into which muons are injected. The size of the vessel depends on the gas pressure. The mean free path of the muon must be shorter than the vessel's diameter. At a pressure of a few dozen atmospheres, the diameter of the vessel where the reactions occur will be about 10 cm. True, in order to be able to use the energy of the alpha particles and neutrons formed by the fusion reaction, the vessel must be enclosed in a thick absorbing layer which must contain lithium to reproduce the tritium. In addition, heat exchangers, generators, and the other standard equipment of electric power plants will be required, all of which are very large. Therefore, it would be hardly possible to obtain a pocket-size muon reactor.

Still a reactor operating with muons could be called a pocket reactor in the sense that

it could be rated for a low power, which would be very advantageous. It is well known that the very high power is one of the difficulties faced by the scientists working on "classical" magnetic confinement reactors. The minimum power at which a "classical" fusion reactor becomes viable from the energy point of view is 5-10 times higher than the power of the largest existing electric power plant.

Alas, our dreams have yet to come true since the main problem remains unsolved.

How Much Do Muons Cost Today?

The minimum energy of about 100 MeV required to obtain a muon is the purely theoretical lower limit. It was calculated very simply: by substituting the mass of a muon (207 electron masses) into Einstein's relation $E = mc^2$, and there you are. However, life has its own laws. In practice, the only known method of obtaining muons is from the decay of a pi-meson, which has a mass of 273 electron masses, and this requires 140 MeV. Moreover, at an energy of 140 MeV the formation of the particles simply starts, while an appreciable rate of formation of pi-mesons is only observed at energies of 300-500 MeV. This must be the energy of protons accelerated in an accelerator and aimed at a beryllium target. The protons knock out a beam of pi-

mesons which rapidly decay into muons.

That is complicated and inefficient from the energy point of view. If we also take into account the efficiency of the accelerator, the situation becomes still worse: about 5000 MeV or even more must be spent to form a single muon.

Uranium Comes to Assistance

In order to make muon catalysis more energy efficient either the energy expenditure needed to create muons must be reduced or the yield of the nuclear fusion energy per muon must be increased.

The first approach requires an improvement in the muon production technology. Some potential for this does probably exist. So far, there was no need for a mass-production of muons, and the technology of this production was not seriously improved, but some potential will perhaps be found in future. At the moment, the second approach looks more promising. Several recipes have already been found. A method for increasing the energy yield has been found and worked out in detail for future fusion reactors based on magnetic traps. The idea is to utilize the ability of neutrons created in the fusion reactions to enter into reactions with uranium or thorium nuclei and so get an additional production of energy.

In addition to the liberation of the extra

energy in these reactions, new isotopes, viz. plutonium 239 and thorium 233, are created. These isotopes can then be used as fuel for ordinary nuclear power plants.

The details of such a hybrid fusion-uranium reactor will be given in Chap. 11. For the present, it is important to note that a hybrid reactor gives a sevenfold increase in the energy per fusion reaction (if we consider the utilization of the nuclear fuel produced in it). The energy production per muon may then reach 14 000 MeV. This is considerably higher than the 5000 MeV that must be spent per muon using today's muon production technology.

Thus, a feasible hybrid muon-uranium reactor could in principle be constructed even today. However, nobody is going to do this now. Work on this project is now in its initial stage. The combination of a synchrophasotron and a uranium reactor does not look elegant in comparison with a pocket reactor envisaged when this idea just emerged. On the other hand, it is remarkable that an idea rejected at the very beginning of the research programme ultimately turned out to be a good one. At any rate, it has already led to a type of reactor that could in principle be built even today.

Chapter 11

Fusion Reactor

The main problems facing controlled nuclear fusion have been outlined. There is no doubt that it should be possible in principle to produce a fusion reactor using advanced techniques of magnetic confinement in toroidal traps (tokamaks and stellarators) and magnetic mirror traps.

Of course, we are only speaking about the possibilities for the time being. The construction of a real reactor would involve a large number of engineering problems. Some of these problems are extremely complicated and their solution is predicted to take one or two decades. Hence the first fusion reactor is not likely to appear before the end of the 1990s or even the beginning of the next century.

A Hop Skip and a Jump

The distance separating us from this goal can be divided into three large stages. The first stage involves the attainment of the appropriate plasma parameters, viz. the temperature, density, and confinement time.

This problem should be solved in the next generation of tokamaks, which are being constructed at present in many countries. These include the T-15 tokamak in the USSR, the TFTR in the USA, the JET in Western Europe, and the JT-60 in Japan. These tokamaks have nearly the same characteristics and size as those of a future tokamak reactor. They will have been constructed by the end of the 1980s, and the main purpose for which these tokamaks are being constructed will have been achieved by then.

The second stage envisages the construction of a demonstration reactor in which the necessary plasma parameters will be attained and all the engineering problems will be demonstrated to be solvable in practice. A positive energy balance will be reached.

This means that, unlike the devices produced in the first stage, the demonstration reactor must possess all the basic elements of a regular reactor and not just a magnetic trap (Fig. 11.1). It must work on a deuterium-tritium mixture so that the intensity of the fusion reactions in the plasma is the same as in a future reactor. This is necessary in order to test the operation of all the components of the device under real conditions of heat flow and neutron emission. It will then be possible to develop the technology for regenerating the tritium by the irra-

diation of lithium with the neutrons arising from the fusion, and to test the strength of materials under a neutron flux more intense than can be created by any other means.

The demonstration reactor must have a system to remove the heat liberated in fusion reactions and to transfer it to a secondary unit for generating electricity. The

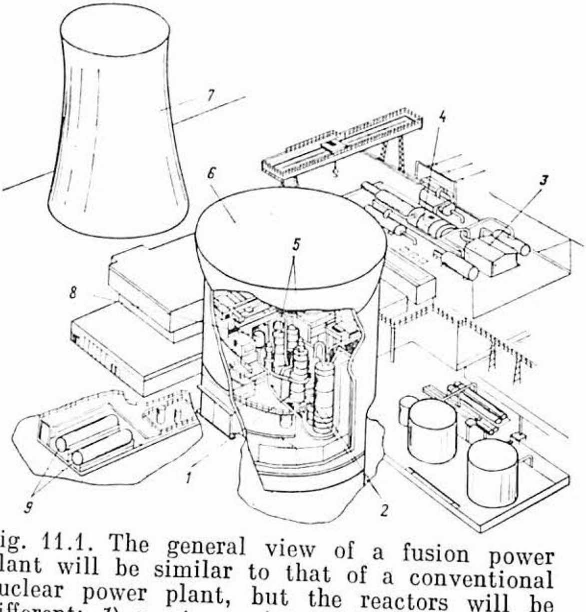


Fig. 11.1. The general view of a fusion power plant will be similar to that of a conventional nuclear power plant, but the reactors will be different: *1*) reactor casing, *2*) heat exchangers, *3*) generator, *4*) turbine, *5*) circulating pumps, *6*) reinforced concrete shell for protection, *7*) cooling tower, *8*) pressure compensator, *9*) drain tanks.

only concession the demonstration reactor may make with a real reactor is that it does not have to compete with other methods for generating electricity in terms of generation costs.

This will be tackled in the third stage. In order to emphasize the importance of the economic aspect of the problem, the third stage in the reactor design is called the "commercial" one.

The construction of a commercial reactor will rely on the results obtained on the demonstration reactor. The task at this stage will be to minimize the installation and operational costs.

The commercial reactor will be a full-fledged power plant and it must demonstrate the advantages of thermonuclear power engineering over conventional electricity generation from the points of view of economy, ecology, radiation safety, etc. If this can be achieved, thermonuclear power engineering will have a long future before it.

The international cooperation over many years in the research on controlled nuclear fusion will be most clearly seen to have been successful at the concluding stage.

As this cherished goal is approached, the reactors will become larger and hence more expensive. Each of the four next-generation tokamaks (the T-15, TFTR, JET, and JT-60) is likely to cost about 200-300 million dollars, while the construction of the de-

monstration reactor is likely to exceed one thousand million dollars, an astronomical figure for scientific research. It is obvious that the construction of several units of this type by a single country would not be expedient.

A few years ago, an International Committee was formed to work on the details of a demonstration reactor Intor (short for international tokamak reactor). This project is well in hand and the blueprint of the reactor has been prepared. After studying the results of the experiments on the T-15, TFTR, JET, and JT-60 tokamaks, it will be possible to start the construction of the Intor. Austria and Finland have already expressed their willingness to provide the land for the Intor in their countries.

How Does a Reactor Work?

Although it is too early to start the construction of a tokamak reactor, its basic design is clear even now. Figure 11.2 represents the cross-section of the main part of the reactor, viz. the tokamak proper. It naturally has a toroidal shape (only the right-hand side is shown). The plasma is located in the very depths of the tokamak and has the shape of an oblate ellipse. The size of the ellipse will be about (2-3) $\times$ (3-5) m^2, and the plasma volume will be

of the order of a hundred cubic metres.

The fusion energy will be obtained in the form of the kinetic energy of the partic-

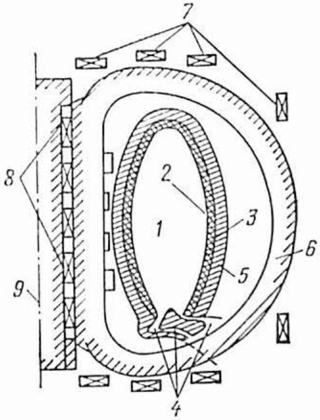


Fig. 11.2. Schematic diagram of a tokamak reactor: *1*) plasma, *2*) first wall, *3*) blanket, *4*) divertor space, *5*) radiation shield, *6*) toroidal magnetic field windings, *7*) control and divertor windings, *8*) inductor windings, *9*) torus axis.

les created in the reaction

$$D + T \rightarrow {}^4He + n + 17.6\ MeV.$$

The alpha particle (${}^4He$ nucleus) only carries away an energy of 3.5 MeV, while the remaining 14.1 MeV goes to the neutron.

The neutrons pass freely through the magnetic field of the trap, and the plasma is surrounded on all sides by a thick layer

of matter (blanket) to stop them. The neutrons give off their energy to this blanket and it is converted first into heat and then into electricity. The alpha particles are captured by the magnetic field of the trap and they gradually transfer their energy to the plasma particles in a sequence of collisions. It is this energy that maintains the plasma temperature required for nuclear fusion. External sources of heat are only used at the beginning of the discharge to bring the plasma to the "ignition" temperature.

The energy liberated in the plasma is continuously transferred to the inner wall of the blanket (*2* in Fig. 11.2) by heat conduction and radiation. This wall is the first one facing the plasma and it must withstand very severe conditions. It interacts directly with the plasma, withstands the radiation and particle fluxes, and fast electrons pass through it. The design and construction of the first wall will be one of the most complicated technical problems in the creation of a fusion reactor.

The helium nuclei formed by the combustion of the nuclear fuel will give off their energy to the plasma and thus they will be converted into a sort of ash which must be removed from the reactor. The plasma particles and radiation falling on the first wall knock out atoms from it that will then become impurities in the

plasma, which should be cleansed from them. This can be done using a divertor (*4* in Fig. 11.2) which is envisaged in the construction of a reactor.

The magnetic field required to confine the plasma will be produced by superconducting solenoids *6*. The most suitable materials for a superconducting solenoids at present are the alloys of niobium and titanium (NbTi) or niobium and tin (Nb_3Sn). These alloys become superconducting at 20 K. This is a very low temperature (—253°C) and considerable amounts of energy must be spent on cooling to such a temperature. Superconducting materials are very sensitive to neutron radiation. Hence, a thick protective layer *5* some 1-1.5 m thick must be wrapped around them. In addition to the solenoids, the magnetic system of the tokamak also contains many control windings *7*. They are intended to regulate the plasma's position and to stabilize the large-scale plasma instabilities using the feedback method. Near the torus's axis, an inductive winding is placed to excite a current in the plasma. The plasma current in the tokamak reactor has a magnitude running into the millions of amperes. However, this current makes an insignificant contribution to plasma heating, and is required in order to obtain the desired configuration of the confining magnetic field.

The inductive winding of the tokamak works on the same principle as an ordinary transformer. The plasma itself is the secondary winding. Current is excited in the plasma by increasing the current in the inductive winding. Hence, it cannot exist all the time, because the current in the inductive winding cannot be increased to infinity. For this reason, the tokamak reactor will operate in the pulsed mode. During the first 5 to 10 seconds, plasma is produced and heated to the ignition temperature. The heat liberated by the current flowing through the plasma is used at first. After the plasma temperature reaches 10 million degrees Kelvin and current heating becomes ineffective, an additional source of heat is used. This may either be a neutral beam or a powerful generator of radiowaves. The additional heating raises the plasma temperature to 100 million degrees Kelvin and fusion reactions occur in the plasma.

The additional heat source can now be switched off and the reactor will work on the heat liberated in the fusion reaction itself. The combustion stage lasts for a few hundred or thousand seconds, i.e. for 10-20 minutes and the current is then switched off. The plasma goes to the first wall (oh, how the poor wall suffers!). The neutral gas formed is pumped out and the chamber is filled with the pure deuterium-tritium mixture. The process is repeated.

Problems, Problems, Problems ...

The main design of a tokamak reactor is therefore clear. Moreover, it can confidently be stated that a plasma will be reliable, and if such a reactor were to be constructed right now, it would operate and have a positive energy balance. We are, however, still unprepared to do it at present. Almost every component of a reactor must be developed from the engineering point of view.

The First Wall

This is, perhaps, the most complicated problem. The first wall is the most vulnerable point in any proposed reactor designs. A universally good solution has not yet been found since many situations must be taken into account.

First, a huge amount of energy flows from the plasma to the first wall. In current designs, the energy flux has a magnitude between 300 and 600 kW/m^2, and so the wall must be cooled to prevent it from melting. It is cooled by water or gas from the side not in contact with the plasma. The removal of such a large quantity of heat this way is not in itself a complicated problem, but the wall must be fairly thin to make sure that the temperature of the plasma side is not too high. If the wall is made of stainless steel, it must not be more than

2 mm thick, although if an aluminium alloy were to be used it could be severalfold thicker. Second, the bombardment of the first wall by the plasma particles will cause the metal to pit, and, given the plasma parameters in the reactor, several millimetres of the wall may be eroded in one year. This means that the first wall must be replaced after one or two years of operation. This will be a very unpleasant job. Apart from the fact that the reactor must be stopped and almost completely dismantled, the wall will be radioactive since it will have been subjected to very strong neutron radiation. The neutrons participate in nuclear reactions with the material of the wall and produce radioactive isotopes. This secondary radioactivity will be so high that the reactor will have to be repaired and the first wall replaced by remote control robots. No one would be able to approach the first wall removed from a reactor for several months or even years.

In addition to the induced radioactivity, neutrons also have other harmful effects. The neutrons will displace the atoms and cause defects in the crystal lattice. As a result, the strength of the materials will decrease. Moreover, protons and alpha particles are formed in the wall as a result of nuclear reactions, these particles will capture electrons from the metal, and will thus be transformed into gaseous hydro-

gen and helium. When the radiation is strong the quantity of these gases will be so large that the metal will bulge out, become brittle, and ultimately be destroyed.

Thermal fatigue will also cause the first wall to disintegrate. During the fusion, the inner surface of the wall will be heated to 500°C. In between the cycles, the wall will cool down to about 300-400°C. These temperature oscillations will cause size oscillations due to the thermal expansion. This will result in thermal stress which can rapidly destroy metal. These factors immensely complicate the construction of the first wall.

Hence, one of the main aims of the International tokamak reactor (Intor) will be to test different materials for the first wall in neutron fluxes approximating the intensity in an actual reactor.

Plasma bursts during disruptions are very dangerous for the first wall. Disruptive instabilities in tokamaks are being intensely investigated, but scientists have so far only succeeded in finding empirical rules for handling plasma and decreasing the probability of disruption; but they have not yet eliminated disruptions altogether. A disruption probability of 0.001 is usually assumed in reactor designs. This means that disruption is expected once every 1000 plasma cycles. Since the first

wall must last about one million cycles, there will be one disruption in 1000 cycles. During such a disruption, the plasma will be partially or completely splashed on the wall. This may be accompanied by the liberation of several hundred joules of energy per square centimetre in some region, which will melt or vapourize several millimetres of wall. To solve this problem, some designs envisage the introduction of an uncooled graphite screen several centimetres thick in front of the first wall. The temperature of this screen will probably rise to 1200-1500°C, but this should not pose any problem for graphite. However, it is not clear how neutrons would react to this screen.

Blanket

We mentioned above that the purpose of the blanket will be to make the maximum use of all the neutrons. Above all, this concerns their kinetic energy. The neutrons produced in a fusion reaction have energies of 14.1 MeV. They easily pass through the thin first wall practically without any loss of energy. To stop the neutrons and convert their energy into heat, a blanket some 0.5-1 m thick must be used.

The reproduction of tritium is the second purpose of the blanket. For this, the following reactions between neutrons and lithium

isotopes are used:

$$^{7}Li + n = {}^{4}He + T + n - 2.8\ MeV,$$
$$^{6}Li + n = {}^{4}He + T + 4.8\ MeV.$$

In the first reaction, the ^{7}Li nucleus disintegrates due to the neutron's energy. In the second reaction, a neutron is captured, and the nucleus disintegrates because it is unstable. This does not involve any energy expenditure. On the contrary, 4.8 MeV of energy is released in the process.

Thus, substances containing lithium must be placed in the blanket to reproduce tritium. Since each of these reactions gives a tritium nucleus, and the neutron liberated in the first reaction can be used in the second, it is possible to obtain more tritium atoms than neutrons by using a mixture of the ^{7}Li and ^{6}Li isotopes in the blanket. In other words, the reactor not only replenishes the tritium it consumes, it also produces tritium which can be used in other reactors. The thermal power of a reactor will be usually 2-5 million kilowatts, and about 10-20 kg of tritium will be consumed annually in the plasma. An equal or even larger amount is produced in the blanket. The plasma itself will not contain more than 0.5 g of tritium.

The radioactivity of tritium poses yet another problem in the construction and operation of the reactor. In order to prevent

tritium from accidentally contaminating the atmosphere and to avoid leaks in the vacuum chamber, the entire reactor will have to be encased in a vacuum dome.

Neutrons Are Also a Valuable Product

In addition to electricity, a fusion reactor will also produce a large number of neutrons, some 3-4 times more than the number produced in a fission reactor of the same power. This is because 170 MeV of energy are released by the fission of uranium nucleus during which only 2-3 neutrons are produced. In other words, 60-80 MeV of energy is produced by fission per neutron, whereas a fusion reactor will produce 17.6 MeV of energy per neutron. True, most of these neutrons will be used to reproduce tritium, but a large number of neutrons will still remain in the reactor and ways must be found to utilize them.

Neutrons are valuable because they induce nuclear reactions. A tempting way to utilize fusion neutrons is to process uranium and thorium isotopes.

The most abundant uranium isotope, i.e. ^{238}U, cannot be used in a conventional thermal neutron reactor because it requires fast neutrons with energies greater than 1 MeV to make it split. A nuclear reactor, like an atom bomb, must use ^{233}U, ^{235}U, and ^{239}Pu. atural uranium, however, contains

0.7% of ^{235}U. The ^{233}U and ^{239}Pu isotopes can be obtained by irradiating ^{232}Th and ^{238}U, respectively, with neutrons.

Uranium ore itself is not expensive and there are developed deposits of it with reserves in the millions of tons. However, the extraction of the ^{235}U isotope, or even the enrichment of the natural uranium in this isotope, is extremely costly. During the enrichment process, the uranium is separated into two fractions, the smaller of which is enriched in ^{235}U and used in nuclear power plants. Most of the uranium is depleted of this isotope and is dumped. Thus, large amounts of uranium containing small amounts of ^{235}U are formed during the operation of a nuclear power plant.

Reactors using fast neutrons (breeders) have been developed in recent years and these both generate energy due to the fission of the ^{235}U isotope and transmute the ^{238}U isotope into ^{239}Pu by neutron irradiation.

The plutonium nuclei can then be used in conventional nuclear reactors along with the ^{235}U isotope. Since the cheap ^{238}U isotope can be converted into plutonium in a breeder the reserves of nuclear fuel become thus much larger. A paradoxical situation arises: a breeder not only generates heat and electricity, it also produces nuclear fuel. What is more, the amount of fuel produced by a breeder is larger than the amount it con-

sumes. This paradox is due to the multiplication of the neutrons during the fission of the ^{235}U nuclei. As a result of irradiation of the ^{238}U nuclei by these neutrons, more than one plutonium nucleus is produced for each disintegrating ^{235}U nucleus.

The use of breeders on a large scale should make it possible, in principle, to utilize the cheap reserves of ^{238}U. However, the pace at which breeders are being built is being held up because they produce plutonium at a very low rate. A typical 10^6-kW breeder produces 70-150 kg of plutonium per year. It will take such a breeder 10-20 years to double the amount of plutonium.

A fusion reactor will thus be much more effective than a breeder. First, it can be charged with pure ^{238}U. Since neutrons are produced in fusion reactions, there is no need to use the valuable ^{235}U isotope or plutonium, which must be consumed in a breeder to obtain the fast neutrons. Second, several times more neutrons are produced in a fusion reactor than in a fission reactor of the same power. Hence, a 10^6-kW hybrid fusion reactor will produce 500 or even 900 kg of plutonium annually instead of 70-150 kg. This means that one such reactor could supply fuel to 3-4 conventional reactors of the same power.

Since hybrid reactors would not require any plutonium, they could be constructed very rapidly.

Figure 11.3 shows a design of a hybrid reactor. It differs only slightly from an ordinary reactor, the main difference being the material comprising the blanket. In

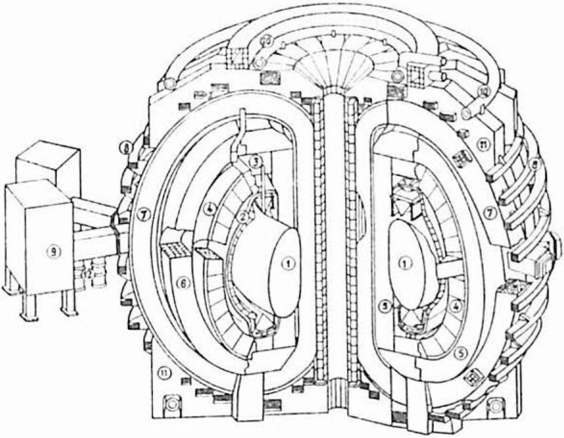


Fig. 11.3. Schematic diagram of a hybrid tokamak reactor: *1*) plasma, *2*) vacuum chamber, *3*) fuel inlet, *4*) blanket containing uranium and lithium, *5*) inner shield, *6*) outer shield, *7*) toroidal field coils, *8*) vertical field coils, *9*) neutral beams, *10*) cooling, *11*) support, *12*) vacuum pumps.

addition to lithium, the blanket of a hybrid reactor would also have uranium in it.

The uranium in the blanket would be in the form of individual hermetically sealed blocks. After two or three years of irradiation, the blanket will contain 1-1.5% Pu.

This will be the optimal duration after which the plutonium should be extracted. The very high radioactivity will mean that all the operations involving the extraction and processing of irradiated uranium will have to be carried out automatically and without the direct participation of human beings.

How to Use Fusion Energy

It might seem strange that we should have to look for ways of utilizing fusion energy. It would be natural to transform it into electricity. We have so far had the tacit understanding that this would be so. It may not, however, be the optimal way of using the energy produced by a fusion reactor. After all, the coefficient of transformation of heat into electricity is much smaller than unity. Besides, the electrical energy cannot be stored for very long. Any electricity generated must be used immediately.

Although there are several methods for accumulating and storing electrical energy, they are still very expensive, and are therefore not widely used. This creates a great deal of inconvenience since we do not consume electricity uniformly. During the day and in the evenings, there are too many users and a shortage of electrical power is always felt. On the other hand, there is a large surplus of electricity at night and

on weekends. Therefore, one of the main problems in power engineering is to work out how to store the energy so that it can be subsequently used in industry, homes, and transport. Perhaps the most fascinating idea on which scientists have been working for many years is to store the energy in the form of the ideal fuel, viz. pure hydrogen.

Pure hydrogen is indeed an ideal fuel. When burnt, it produces pure water and nothing else. Hence the problem of environmental contamination is eliminated. The calorific value of hydrogen is much higher than that of conventional fuel. The storage and safe handling of hydrogen presents no more difficulty than that faced to handle gas or petrol, and practical solutions have already been obtained for these problems. Cars running on hydrogen have been successfully tested on road. The only drawback hindering the use of hydrogen as a universal fuel is the high cost of its production.

The cheapest source of hydrogen today is natural gas. However, extracting hydrogen from natural gas also costs money, and hence it is more economical to burn the natural gas than to extract the hydrogen.

Water is a natural source of hydrogen. Unfortunately, the water molecule is one of the strongest molecules, and it only dissociates into hydrogen and oxygen at very high temperatures (exceeding 5000°C). It is

not easy to attain such a high temperature. It can be done in an electric furnace or electric arc. But this is less economical than direct electrolytic dissociation. Hydrogen is obtained directly in pure form by electrolytic dissociation. However, this process turns out to be four times more expensive than burning an equivalent quantity of conventional fuel.

When controlled nuclear fusion research began to reach its final stage, and detailed designs for fusion reactors began to appear, it became clear that here, at last, was a source of heat ideal for the production of hydrogen. After all, there must be a region with a temperature of 5000°C somewhere between the plasma heated to 100 million degrees Kelvin and the cold outer walls of the reactor, and in this region water will thermally dissociate. Calculations show that a reactor with a thermal power of 10 million kW would annually produce about a million tons of hydrogen. The utilization efficiency of the reactor's energy would then be 0.57, which is much higher than that for the generation of electricity. Thus, the development of thermonuclear power engineering not only would help in generating electricity, it would also help solve an ecological problem.

What about Tritium and Neutrons?

Tritium is radioactive. Hence, considerable attention must be paid while designing a reactor to the prevention of tritium accidental leakage to the atmosphere.

However, as has been said earlier, the amount of tritium in the plasma would be very small (less than a gram), and hence there is not much danger due to the tritium. The blanket and the tritium reproduction system will be much more hazardous. These contain several kilograms of tritium. However, the atom here is chemically bound and so would hardly be likely to leak into the atmosphere in the case of an accident.

The radioactivity induced by the neutron irradiation of the reactor's components poses a much more serious threat. For example, when steel is irradiated by neutrons, radioactive isotopes of iron, cobalt, nickel, and manganese are formed. They are several hundred times more radioactive than tritium.

In a hybrid reactor, the radioactivity will be mainly due to the fission products of uranium. This radioactivity will be an order of magnitude higher than that of the reactor's components. Thus, the level of radioactivity in a hybrid reactor will be the same as that in a conventional nuclear reactor.

Ten hours after switching a fusion reactor off, the radioactivity in it will be about 1/25th that in a fission reactor of the same power. If the radioactivities of the two reactors are compared much later, the difference will be even larger. After 100 years, the radioactivity in a fusion reactor will be 1/300th that in a fission reactor. This is because a fusion reactor does not produce any long-lived isotopes such as plutonium, strontium, and cesium.

The Economics

The development of thermonuclear power engineering naturally depends on its viability in comparison with other sources of energy. When investigations on plasma confinement and heating revealed that controlled nuclear fusion is possible in principle, a serious feasibility study was carried out for the generation cost of electricity in a fusion reactor and of its viability vis-à-vis other power sources. Feasibility projects for fusion power plants with cost estimates for their construction and operation were presented.

So long as materials and components used in nuclear reactors are not produced in bulk they are very costly. Hence, the construction of the first fusion power plant will be 2-2.5 times more expensive than the cost of a conventional nuclear power plant of

the same power. With the passage of time, the relevant industries will develop and the installation cost of fusion power plants will fall. Moreover, a considerable fuel saving can be achieved. A conventional power plant rated at a million kilowatts and operating on petroleum or coal consumes millions of tons of fuel annually, which cost enormous sums of money. A fusion power plant will only work on deuterium (i.e. water), since the tritium is reproduced during the operation of the plant.

A few cubic metres of water a day will be all that is required to ensure the fuel supply to a fusion plant rated at a million kilowatts.

Naturally, the extraction of deuterium from water will not be carried out at the power plant itself. This will be a centralized facility for all the power stations in the country. The process has been thoroughly developed and is so cheap even today that the cost of deuterium is much lower than that of conventional fuel.

Since the installation costs of larger power plants are lower, the viability of fusion power plants increases with their capacity. Hence, it would be best to construct very large power plants with capacities of 10 million kilowatts or more. Power engineers have still to work out how to control units with such large capacities.

From the point of view of electrification,

the fusion reactors have another significant advantage in that they can be constructed anywhere. They do not require railroad system to transport fuel. On the other hand, the safety and ecological cleanliness of fusion power plants mean that they can be constructed close to large cities, i.e. near the consumers. This will save the considerable expenses on electric power lines.

Conclusion

Surveying the three decades that have been spent on investigating controlled nuclear fusion, and the prospects for the next 15 or 20 years that will be needed to achieve practical results in the field, we might get the impression that progress is extremely slow. This would, however, be deceptive. As a matter of fact, considerable advances are being made every year.

Even as this book was being written, significant progress has been made in all the main approaches to controlled fusion.

Tokamaks. In the tokamak investigations, most attention in recent years was focussed on plasma heating by radiowaves. This method is much more economical than that of fast atomic beams, which was first used in the PLT experiments, during which the plasma was heated nearly to the fusion temperatures. Hence it should be expected that plasma heating to the ignition temperature in the fusion reactors of the future will be done by radiowaves and recently radiowave generators with megawatt power have been used at the largest experimental units.

Soviet scientists have made some remarkable progress in the plasma heating by radiowaves. The electron temperature of the plasma in the T-10 tokamak was raised to 45 million degrees Kelvin using six gyrotrons having a total power of 0.8 MW. This experiment was based on electron cyclotron resonance, in which the frequency of the radiowaves coincided with the rotational frequency of the electrons in the magnetic field.

In terms of economics, this result is better than the famous record heating of plasma by fast atomic beams in the PLT tokamak. The latter required a power of 2.4 MW (which was three times greater than that needed on the T-10) to raise the plasma temperature to 60 million degrees Kelvin. However, the plasma density in both experiments was considerably lower than that required for a fusion reactor. American scientists have made significant progress in increasing densities on the Alcator C tokamak with a very strong magnetic field. Using a 1-MW radiowave generator, they were able to heat a plasma with a density of 2×10^{20} m^{-3} (which is the value required for a fusion reactor) to a temperature of 33 million degrees Kelvin.

Whether a future reactor will be economic depends to a large extent on the parameter β, viz. the ratio of the plasma pressure to the pressure of the magnetic field. The value

of β must be at least 8-10% in the reactor. For the time being, it is just about 1% or even less. Theorists point out that an increase in the value of β will give rise to a number of problems which will hamper the plasma confinement in a tokamak. If the plasma is treated as a gas, its pressure is defined as the product of its density and temperature: $P = nT$. Hence β can be increased by increasing the plasma density and the temperature. In other words, an increase in β is not only associated with the problem of confinement, it also depends on the possibilities of plasma heating.

On the other hand, the value of β could also be increased by decreasing the magnetic induction. Such experiments have already been carried out on existing installations. Plasma confinement experiments using this method were carried out on the Soviet T-11 tokamak and the American Douplet III tokamak. Contrary to the predictions of the theorists, the plasma was confined in these experiments at β values up to 4.5%.

A significant step forward in the tokamak programme would be to get rid of the pulsed mode of operation, which is necessitated by the inductive method of exciting a current in the plasma. For this purpose, experiments have recently been carried out on many existing units to sustain the current in the tokamak plasma by radiowaves. Significant advances have been made by

Soviet and Czechoslovakian scientists, who obtained a current up to 200 kA on the T-7 tokamak, and by American scientists who were able to sustain a current of 160 kA in the PLT tokamak for full four seconds with the help of radiowaves.

The construction of the next-generation tokamaks, viz. the Soviet T-15, the American TFTR, the West-European JET, and the Japanese JT-60, is under way. These huge devices must demonstrate that the basic fusion parameters, viz. the density, temperature, and confinement time of the plasma can be attained.

The West-European JET tokamak and the American TFTR tokamak have already been assembled. Plasmas have already been generated in them, although no methods for additionally heating them have yet been used. Hence, the plasma is fairly cold by existing standards and the electron temperature is only about 10 million degrees Kelvin. However, an impressive confinement time of 0.3 s has readily been achieved owing to the large dimensions of the devices. During the assembly of the powerful generator needed to supply the electric current to the main magnetic field winding on the TFTR tokamak, a rare accident took place: the hook of the crane straightened, and the rotor of the generator, w hich had a mass of about 200 tons, fell onto the stator and damaged it. It was one of two

such generators. Thus, the TFTR is now operating at only half of the planned magnetic induction.

Individual components and blocks of the Soviet T-15 tokamak and the Japanese JT-60 tokamak are still under construction. The Soviet tokamak will have a superconducting solenoid made of Nb_3Sn, but such solenoids take a long time to build and are complicated.

Experiments on all four units will probably be carried out in full swing within the next couple of years. By the end of the decade, fusion conditions will have been realized, and the output of fusion energy in the plasma will exceed the energy supplied to it.

Stellarators. Intensive studies of plasma heating by radiowaves have been started on stellarators in the same way as on tokamaks. However, the generators for the stellarators only have powers of 100-200 kW. Accordingly, the results are still quite modest, with the electron or ion temperature rising to about 7-10 million degrees Kelvin. These results were obtained on the Soviet L-2, the Japanese Heliotron-E, and the German Wendelstein-7A stellarators.

As a matter of fact, the achievements using stellarators are much more impressive because the experience with tokamaks indicates that plasma heating is just a matter of power. So far as plasma confinement is

concerned, significant achievements have been made with stellarators in recent years. We mentioned in Chap. 8 that the plasma confinement time in stellarators rises sharply when the latter operates in the currentless mode, and no current distorting magnetic field passes through the plasma. Recently, even more significant results were achieved in stellarators. For the first time in tokamak and stellarator research, the energy confinement time was found to be in line with the predictions of neoclassical theory.

This theory takes into account the effect of magnetic field structure and collisions between particles on the motion of plasma particles. The Soviet scientists R.Z. Sagdeev, A.A. Galeev, B.B. Kadomtsev, V.D. Shafranov, and L.M. Kovrizhnykh have contributed significantly to this theory.

The neoclassical theory only takes into account unavoidable heat losses by the plasma and its predictions give the minimum values for the rate of heat loss from the trap. Usually, the real rate of heat loss is an order of magnitude higher than the predictions of neoclassical theory because of incompletely suppressed instabilities, distortions in the magnetic field structure of the trap due to currents flowing through the plasma, and other reasons which are still unclear (this situation prevails even today in tokamaks).

In the light of this, the agreement between the energy confinement time in stellarators and the values predicted by neoclassical theory means that a calm plasma has at last been obtained in stellarators and that its behaviour can be completely predicted.

This outstanding result was obtained through simultaneous development of theory and experimental technique. On the one hand, L.M. Kovrizhnykh was able to take into account more thoroughly how the electric field produced in the plasma due to the difference in the rate of escape of electrons and ions from the trap affects the plasma confinement. On the other hand, the experimental energy confinement time was considerably increased by using the currentless plasma mode.

If the plasma could be kept calm in a stellarator even when the density and temperature approach fusion values, a stellarator reactor would be very economical indeed.

Magnetic mirror traps. The most significant recent development is associated with the concept of a tandem trap. Experiments on the Soviet Ambal trap, the Japanese Gamma-6, and the American TMX have confirmed the basic idea: the introduction of additional traps with higher plasma densities at the ends of the main trap leads to the emergence of a strong electric field,

which improves the ion confinement in the main trap.

Further research on tandem traps is going on to improve the plasma parameters and decrease the specific losses in sustaining the required electric field. Another small magnetic mirror trap filled with a very hot electron plasma and called a thermal barrier is introduced between the main trap and the additional end trap. Hot electrons enter the central trap and maintain a negative potential in it, which is required for the ion confinement. With the thermal barrier, one can use much smaller plasma density in the end traps than that required in a simple tandem trap. Traps based on the idea of the thermal barrier have already been constructed.

Pinches and plasma focus. Research on plasma focus is aimed at increasing the energy supplied to the discharge. Units with energies up to 1 MJ have already appeared. A neutron yield of up to 10^{12} neutrons per pulse has been obtained for such an energy on the Italian Frascati-1 device. The weak point of the plasma focus technique continues to be the short confinement time: as before, the value of $n\tau$ is about 1/1000th of Lawson's criterion. However, plasma focus technique is being studied in many countries independently of the application to fusion because it promises to be a very cheap source of neutrons.

Several new ideas have also appeared concerning pinches, one of the oldest aspects of fusion research. A hybrid unit, called Kollaps, has been set up at the Efremov Institute of Electrophysical Apparatus in Leningrad. It consists of a powerful CO_2 laser TIR-1M and the Utro theta pinch. The idea of the experiment lies in the generation and preliminary heating of the plasma by the laser and in the subsequent compression of the plasma in the theta pinch. Calculations show that the plasma temperature at the moment of the maximum compression can be increased fourfold in this way.

Inertial confinement. Laser fusion research is now being carried out with units having pulse energies up to 10 kJ. The recent American Nova unit uses 100-kJ laser. This is a significant step in the right direction, but the laser energy is still insufficient. The energy required to initiate a fusion reaction with inertial confinement is still of the order of megajoules. Hence the idea of replacing the lasers by powerful accelerators is drawing considerable attention.

High hopes are being pinned on the development of accelerators of light ions like lithium and beams with energies of 1 MJ have already been obtained. This value is likely to be raised to 4 MJ in the near future. The initiation of fusion reactions by light atomic beams requires an estimated energy of about 10 MJ. Hence, light

ion beams are closer to the target than lasers.

Reactor designs. The encouraging results obtained in the experiments on plasma heating and confinement in magnetic traps have stimulated the design of experimental fusion reactor. This has been going on for many years now in all leading countries both under the project of the international reactor Intor and under their respective national programmes.

Discussions on an experimental fusion reactor have already begun in the USSR. It will probably be a hybrid fusion reactor. The plasma heated to the fusion temperature will be surrounded by a layer of the cheap ^{238}U isotope so that the neutrons produced in the fusion reactions can convert it into the valuable ^{239}Pu isotope. This isotope can then be used to produce energy at a conventional nuclear power plant. The power production can be increased by a factor of 5-7 with the help of this method. The plasma confinement conditions can be made less stringent accordingly. This may turn out to be very important for the first reactor in view of the fact that the plasma confinement problem has not yet been solved completely.

The first fusion reactor will probably be a tokamak with the following dimensions: the radius of the torus 5-6 m, the plasma radius slightly more than 1 m, and the

plasma volume 250-300 m^3. The thermal power of the experimental fusion reactor will be about 1000 MW. For a 30% efficiency of conversion of heat into electricity, the electric power of an experimental fusion reactor will be 300 MW, of which 200 MW will be consumed by the reactor itself. The reactor will supply 100 MW of electricity to the external circuit, 700 MW of heat, and 200 kg of plutonium per year.

Specialists believe that if investigations are carried out quite intensely, an experimental fusion reactor may be ready by 1996.

To the Reader

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SCIENCE FOR EVERYONE

The energy we get from the Sun is generated at its core in fusion reactions, in which hydrogen is turned into helium. If these reactions could be used on Earth, humanity would be able to provide itself with an abundance of energy. The problem of maintaining practical nuclear fusion has been one of the central problems of physics for some thirty years, and yet only now has it become clear that a solution is in fact possible. This book explains in a lively and informal way how the investigations have developed, the cleverness of the ideas used to tackle the problems, the ingenuity behind the experiments, and the successes and setbacks encountered in dealing with the capricious and cunning material we call plasma.

Intended for teachers, college students, and school pupils.

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